

The Effect of Thickness and Continuity of Motorcycle Helmet Shells on Performance

by

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Dissertation submitted in partial fulfillment of the  
requirements for the degree of Masters of Science in the  
Department of Biomedical Engineering in the  
Graduate School of Duke University

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ABSTRACT

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## **Abstract**

Road accidents are the leading cause of death within the 15-29 years age range worldwide and the risk of death for motorcyclists is 20 times that of car occupants. As such, 31% of over 10,250 annual road traffic deaths in Uganda are due to either 2 or 3-wheeler motorists' accidents. Another study in Uganda revealed that 71% of its motorcycle crash victims sustained a head injury while more research shows that helmets can reduce risk of death by 37% and risk of head injury by 69% in the event of a crash. Unfortunately, helmet-use compliance is 30.8% and 1% compliance for riders and passengers respectively in Uganda. Market research by Design without Borders and the Uganda Helmet Vaccine Initiative, attributes this low helmet-use to discomfort, poor helmet ventilation and the prohibitive price of the helmets. A large part of the prohibitive helmet price is due to onerous performance requirements which drive up the development and manufacturing costs. One such requirement is ensuring the helmet's optimal performance in temperatures as low as  $-20^{\circ}$  Celsius which are atypical in tropical climate regions. Another is that the helmet withstands multiple identical impacts at exactly the same location which is extremely rare in a crash. This Masters research is concerned with investigating the effect of continuity and thickness of motorcycle helmet shells on performance. Helmeted head impacts were simulated at three impact points using two different impact surfaces while varying shell thicknesses and continuity using LS DYNA, a Finite Element Analysis software. Increase in shell thickness reduced motorcycle helmet performance while splitting the shell in halves did not significantly affect motorcycle helmet performance. Insights from this research will inform and guide the engineering design of affordable market approved, better ventilated motorcycle helmets under 10 USD that will be suited for the Tropics.

## **Dedication**

I dedicate this Masters thesis dissertation to my mother, Norah Nalweyiso Serunjogi and my late father, Henry Mbabazi Bagarukayo.

Mum, among many sacrifices, you gave up your scholarship to medical school to bring us up right with true appreciation of hard work and self-belief. This Masters of Science in Biomedical Engineering dissertation is one of many testaments-to-come embodying these values. Thanks mum! This one is for you. Cheers to single moms.

And to my late Papa, while you were gone before the number line made any sense to me, what I heard about you inspired me to reach this feat. Your climb from studying barefoot in the humble Kabale hills to thriving in the renown Leeds University and the University of Alabama pushed me strive to walk in your footsteps. Your shoe size is still big, but again, this is just the beginning. This one is for you, Dad as well.

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To Prof. William Reichert, the Department of Biomedical Engineering at Duke University in its entirety, I cannot thank you enough. The scholarship you awarded me has opened many doors not just for me, but for the many lives I will touch post Duke. I am forever indebted and thankful for your generosity and flexibility in making the Makerere-Duke partnership a success.

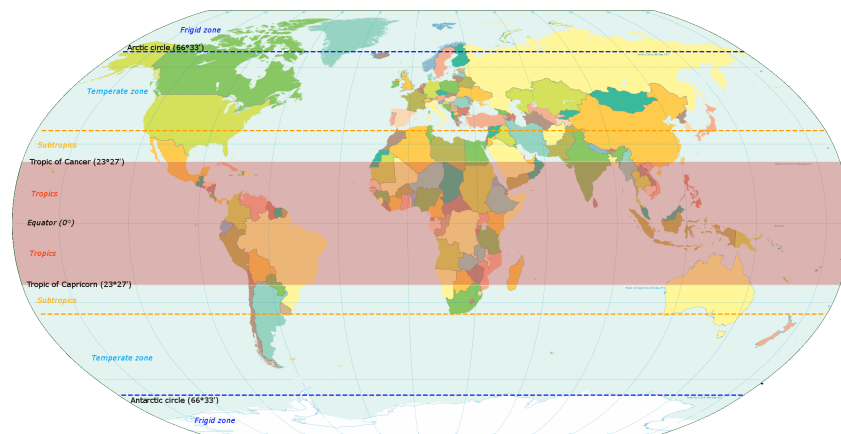
To my thesis committee and colleagues. From you, I got constructive feedback that refined the work presented herein and the man I am today. The saying, "A friend in need is a friend indeed" summarizes my heartfelt gratitude to you.

*May the Good Lord Bless You All Abundantly*

# 1. Introduction

## 1.1 The Tropical Region

The Tropical region, also commonly referred to as the Tropical belt or zone, is a climatic region bound between the Tropic of Cancer and the Tropic of Capricorn as shown by the picture below. It is comprised of countries and territories in North America, Central America, South America, the Caribbean, South-East Asia, India, East Africa, Central Africa and parts of West Africa. It is distinguished by its generally hot and wet climate all year round from other climatic regions.



**Figure 1: The Tropical Belt**  
(Source: Wikipedia, Picture credit to KVDP)

The Tropical belt is home to 40 % of the world's population.<sup>1</sup> All but two of the 101 countries and territories which comprise the Tropical region have Low and Middle-Income Status.<sup>2</sup>



rainfall amounts range from 900 to 1600 millimeters with the averages ranging from 1000 to 1500 millimeters received in a biannual pattern from March till May and October till November.<sup>3,4</sup>

According to the 2014 National population Census, Uganda has a population of 34.9 million most of whom depend on agriculture for a livelihood. It has the second youngest population in the world after Niger with a median age of just 15.9 yet 70% of all Ugandans who enroll in primary school dropout before completing it.<sup>4,5</sup> As such, most youth depend on odd jobs for a living.

### **1.3 Scope of the Problem**

Worldwide, Road Traffic Accidents (RTAs) account for about 1.25 million deaths annually and are the leading cause of death in the 15-29 age range yet 90% of RTAs occur in Low and Middle-Income Countries (LMICs).<sup>6</sup> If not addressed, by 2030, RTA deaths will be the seventh leading cause of death, higher than HIV/AIDS, Malaria and Tuberculosis deaths.<sup>6,7</sup> Nearly half of RTA deaths are among pedestrians, motorcyclists and cyclists.<sup>6</sup> Additionally, every year, about 20 to 50 million Disability- adjusted life years (DALYs) are lost globally due to RTAs injuries, 90% of which are lost in LMICs.<sup>8,9</sup>

In 2002, 73% of all RTA deaths and 70% of RTA injuries worldwide were male.<sup>9</sup> A 1997 review of epidemiologic studies on RTA injuries by Odero et al revealed that in developing countries, nearly 80% of RTA casualties are male.<sup>10</sup> Owing to the unfortunate global gender inequality, men currently contribute more to the combined household income than women so high RTA deaths destabilize families and consequently slow development at a national level.<sup>11</sup>

As such, LMICs incur USD 65 Billion, (about 12.5%) of the global cost of managing RTAs and its associated Injuries, an enormous financial burden considering their Low and Middle-Income Status.<sup>12</sup>

This high prevalence of RTAs in LMICs is attributed to overloading, non-use of safety belts and motorcycle helmets, utilization of very old vehicles prone to malfunction, low enforcement of and abiding to traffic laws and inadequate transportation- infrastructure due to a higher influx of vehicles than new transportation infrastructure set up.<sup>13</sup>

Motorcycles are very popular in LMICs because they are cheaper, easier to repair when they break down, require less fuel and in the urban areas particularly,

because they are easy to maneuver through the dense traffic jam during rush hours in addition to requiring lower fares. As such, the motorcycle taxis business is a booming industry for many.

In Uganda, motorcycle taxis – boda-bodas as they are locally called – are the most popular means of transportation employing 100,000 drivers most of whom are male youth.<sup>13</sup> A 2017 WHO report on road safety states that about a third of road accidents in Uganda are due to either 2 or 3-wheeler motorists.<sup>6</sup>

The risk of death for motorcyclists is 20 times that of car occupants on the road, yet according to the WHO, 41 of Africa's 54 countries either have no comprehensive helmet law or have no helmet law at all.<sup>14,6</sup> Uganda is one such country with a law that mandates every rider to wear a helmet but it is under implemented. A recent helmet-use compliance study in Uganda found 30.8% and 1% compliance for riders and passengers respectively which in part is responsible for the high percentage of motorcycle crash victims (71%) who sustain head injuries according to a study conducted in the Uganda Mulago National Referral Hospital.<sup>15, 13</sup>

Market research by Design without Borders and the Uganda Helmet Vaccine Initiative, attributes Uganda's low helmet-use to discomfort, poor helmet ventilation and the prohibitive price of the helmets.<sup>15,16</sup>

True to the acronym "*Prevention is better than cure,*" Uganda only has 5 of East Africa's 27 neurosurgeons serving a population of over 30 million people so it is inevitable for motorcycle head-injury patients to receive delayed emergency care which could lead to death.<sup>17</sup>

A Center for Disease Control study found that motorcycle-helmet use reduces risk of death by 37% and risk of head injury by 69% in the event of a crash.<sup>18</sup> As such,

the high efficiency, cost effectiveness and short duration of execution make increasing helmet-use the go-to solution to curb the high motorcycle-crash mortality and related injuries in LMICs.

Design without Borders came up with a helmet design that has grooves in its foam liner and holes in its shell for ventilation to maintain the temperature inside the helmet within an agreeable range to the riders. They also conducted a feasibility study on different aesthetic designs of motorcycle-helmets until a market-approved helmet design ideal for Ugandan riders was arrived at. The pictures below show two Design without Borders market-approved “BePro” helmet designs.



**Figure 3: Design without Borders market-approved “BePro” motorcycle helmet designs.** (Source: Design Without Borders)

A large part of the prohibitive helmet prices is due to onerous performance requirements by the European, Economic Commission for Europe (ECE) and the American, Federal Motor-vehicle Safety Standards’ (FMVSS 218) Helmet standards which drive up the manufacturing and design costs of motorcycle helmets (Luck et al,



2017 in review). One such requirement is ensuring the helmet's optimal performance in temperatures as low as -20° Celsius (European standard) and -15° Celsius (American standard) which are atypical in tropical climate regions.<sup>19</sup> The other is that the helmet withstand multiple impacts at exactly the same location which is extremely rare in a crash.<sup>19,20</sup> The European motorcycle helmet standard was passed in 1958 in agreement with the United Nations.<sup>19,20</sup>

The United Nations, however, has not published a motorcycle-helmet Standard for the Tropical region yet the difference in climate between the Tropics and Europe has price-significant implications on the unit cost of the helmets: it forces engineers to use more expensive materials in the helmet designs which may also require more complex manufacturing processes. Consequently, Tropical countries adopted or adapted either the European or the American motorcycle helmet standard at the expense of helmet affordability and ventilation.

The unaffordability of these standards' certified motorcycle helmets in the Tropics has caused an influx of non-certified helmets on the market that typically cost in the range of 10-15 USD in comparison to the certified helmets which typically cost in the range of 30-40 USD (Luck et al, 2017 in review). The influx of uncertified helmets in the Tropics is enabled by a lack of a manufacturer-independent system to enforce the standards. In-part, this is due to the high set-up costs of helmet testing labs. A study that is still in review conducted at the Duke University Injury Biomechanics lab by Luck et al compared the level of safety of uncertified helmets and certified helmets and found their performance to be similar in most cases while in a few cases the uncertified helmets actually performed better! Luck et al (in review) also reports that in Vietnam, riders are

willing to pay about 17 USD for a motorcycle helmet. Therefore, a 40-dollar helmet would be more than twice what they can afford!

Another significant contributor to the unaffordable helmet costs in the Tropics is the lack of helmet manufacturing capacity in-country. In this light, the helmets have to be shipped, mostly from Asia, thereby increasing the cost per unit considerably.

Consultation with US based Engineering Design Firm with manufacturing connections and experience in Asia for over 25 years and supply chain distribution in the Tropics, AirSpeed llc, advised that shipping costs could contribute up to 15% of the eventual helmet cost in the Tropics. A standard 2.43 by 2.59 by 6.06 meter shipping container fits about two thousand seventy 0.258 by 0.257 by 0.254 Gomet motorcycle helmets while the same container would fit over fifty three thousand helmet shells stacked in halves.<sup>21</sup> In this light, AirSpeed LLC recommended research of splitting helmet shells.

This Masters thesis research employs Finite Element Analysis to study the effect of thickness and continuity of motorcycle helmet shells on performance per the research hypotheses below. The objective of this research is to guide design of cheaper helmets affordable by Low and Middle-Income earners.

- 1) Splitting the helmet shell along the mid-sagittal plane will not significantly affect the safety of the helmet.
- 2) Varying Shell thickness will significantly affect the safety of the helmet.

Finite Element Analysis is an engineering tool used to numerically test behavior of computer-built models (CAD models) when subjected to physical phenomena in the virtual computer realm. Specialized Finite Element Analysis (FEA) software is used to approximate, often with dependable veracity, how the CAD model would perform in the

real world. The CAD model is meshed into many small elements to enable numerical analysis during the simulation.

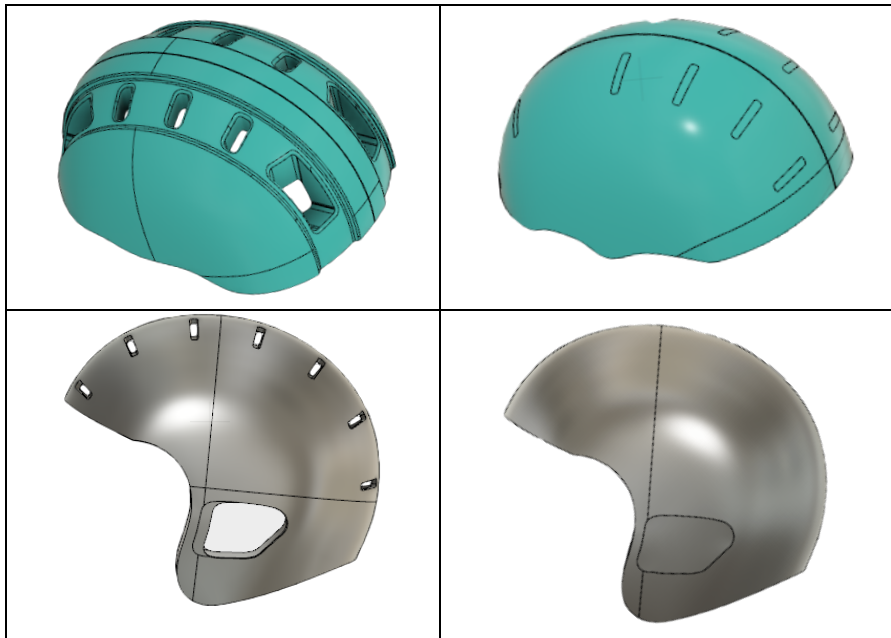
LS-DYNA software by Livermore Software Technology Corporation (LSTC) is one such FEA software that was used to simulate typical motorcycle crash impacts in this research. An open-source, FEA FMVSS-certified Hybrid III 50<sup>th</sup> Percentile male, crash-test head-dummy model, developed jointly by the National Crash Analysis Center (NCAC) at George Washington University and LSTC was used to investigate the research hypotheses above in accordance to the American FMVSS 218 Motorcycle Helmet Standard.<sup>22</sup>

LS DYNA has two parts: LS PREPOST for preparing the model for numerical processing and viewing the results post processing, and LS DYNA Manager for the actual numerical processing. Typically, keyword files (extension. k) are exported from LS PREPOST, ideally saved in a separate folder, and then run using the LS DYNA Manager Solver. A normal termination means the results are saved in the folder and are ready for analysis in LS PREPOST while an error termination means there was an error in the Pre-processing stage.

## 2. Methods

### 2.1 Pre-DYNA CAD modelling

A conceptual CAD model of the BePro helmet by Design without Borders was modified in Fusion 360 CAD modelling software to optimize it for FEA simulation. In essence, the modification involved converting the conceptual BePro helmet CAD models to editable engineering CAD models. Additionally, the BePro CAD model was simplified by removing all holes, deleting ear pads, removing the helmet ridges and removing the grooves in the liner. These simplifications were done to avoid very small element sizes to occur during meshing. These usually arise along very small dimensions and they often considerably increase simulation run-time and/or cause the simulation to fail. The optimized BePro helmet was exported as an IGES (extension. igs)- the only readable format by LS DYNA- from the Fusion 360 website.

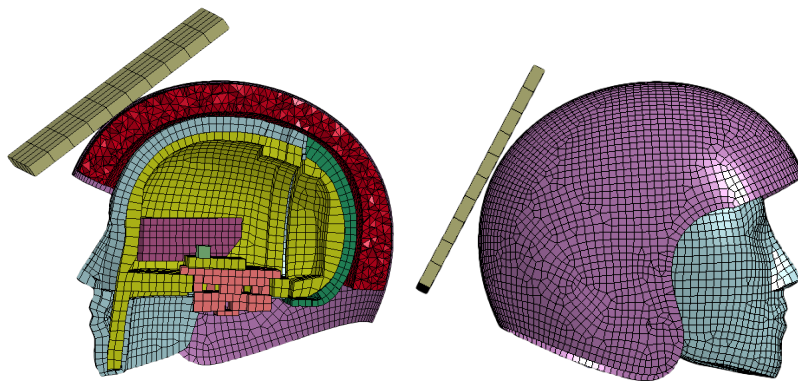


**Figure 4: The BePro liner and Shell before (left column) and after (right column) CAD modelling modifications for FEA optimization.**

## 2.2 DYNA Preprocessing

A cuboid of 200 by 200 by 10 mm and a sphere of radius 4.8 cm was CAD modelled in LS-DYNA Prepost in accordance to the American helmet standard. The spherical impact anvil is referred to hereafter as the round anvil. The open-source FEA NCAC-LSTC Hybrid III 50<sup>th</sup> Percentile male crash test dummy head model was then assembled with the optimized BePro CAD model in LS-DYNA PrePost resulting in a helmeted head dummy assembly as shown by Figure 5 below.

The assembly was then meshed by part to a mesh size of 4 mm: The helmet shell was meshed with 2-D shell elements while the rest of the parts were meshed with solid tetrahedral elements as shown in the Figure below.



**Figure 5: A helmeted head form assembly**

Thereafter, materials were assigned to the different parts as shown by the table below

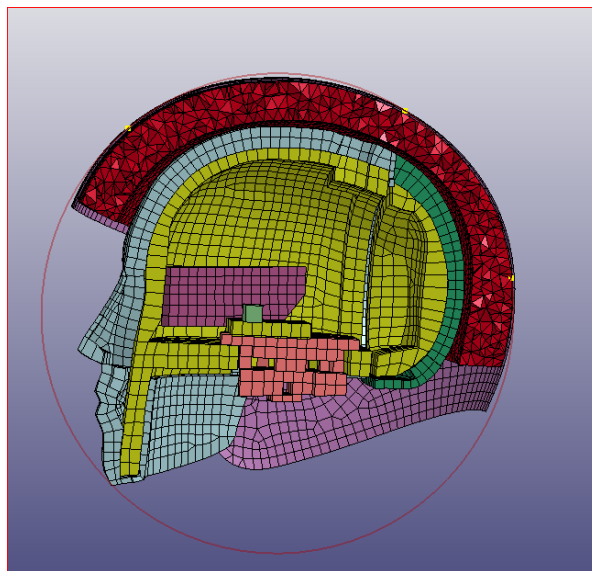
**Table 1: Materials used in Simulation**

<b>Part</b>	<b>Material</b>	<b>LS-Dyna Material ID</b>
Shell	Polycarbonate (Deformable)	40
Liner	Expanded Polystyrene (112gm/L) (loading curve in appendix)	84
Flat and round anvils	Steel (Rigid)	1
Head Skin	Vinyl (Deformable)	66
Head Cap Skin	Vinyl (Deformable)	66
Head Skull	Aluminum (Rigid)	20
Head Ballast	Steel (Rigid)	20
Head Base	Steel (Rigid)	20
accelerometer	Steel (Rigid)	1

Contacts were then assigned to define the interaction of the geometries as described below. Automatic Surface to Surface contacts were defined between; the skin of the head and the liner, the shell and the impact anvil, and the liner and the flat anvil. The liner to anvil contact was defined to accommodate the cases when the shell was split. Without this contact, liner elements would have penetrated the anvil. To simulate the glue between the liner and the shell, a Tied Surface to Surface contact was defined between the liner and the shell. All of the contact keywords are attached in the appendix.

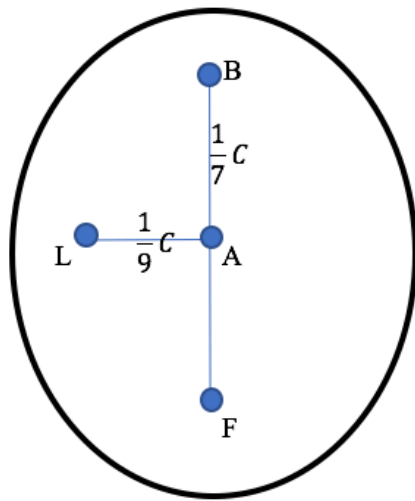
A uniaxial initial velocity of 6.0 m/sec was then assigned to the whole helmeted head assembly to impact the flat anvil and a 5.2 m/sec uniaxial velocity to the round anvil in accordance to the American helmet standard.

The American helmet standard requires impacts at three different locations. To find the center of rotation of the helmeted head to enable change of impact location, the helmeted head was approximated to be spherical. It was cut along the mid-sagittal plane and the closest-fit circle was traced along three points on the shell periphery. The node of the center of the circle was noted and consistently used as the center of the rotation when the helmet had to be re-aligned to impact any one of the three different impact locations- side, front and back.



**Figure 6: Finding center of rotation of helmeted head. Approximating helmeted head to be a sphere and finding the center node of the circle along the mid sagittal plane.**

A configuration of finding impact points in a manner that satisfies American helmet standard's requirement to have at least a sixth of the maximum circumference impact-point separation was adopted from, Luck et al, 2017 (in review) as shown below.



Reference Point

A- Apex

Impact Points

F- Front

B- Back

L- Left

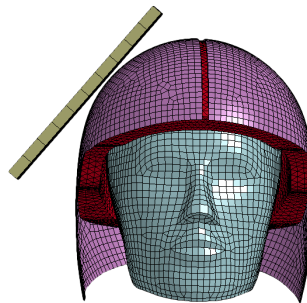
Distances

$A:B = A:F = \frac{1}{7} \text{ Circumference of helmet } (C)$

$A:L = \frac{1}{9} \text{ Circumference of helmet } (C)$

**Figure 7: Impact location configuration. The Left Impact point is referred to as the Side Impact location hereinafter. Points FAB are located along the mid-sagittal plane, while points LA are located along the mid-frontal plane.**

Shell thickness, shell continuity and impact locations were varied during the simulations. Shell thicknesses were varied from 0mm to 5mm in increments of 1mm since typically, shell thicknesses range from 1 to 4 mm. To simulate the effect of splitting the shell into two halves, one column of elements along the mid sagittal plane was deleted (Figure 7).



**Figure 8: A helmeted head form showing the split shell along one column of elements along the mid-sagittal plane.**



Impact locations and anvils were changed by a combination of rotations and translations done at a predefined center of rotation to ensure; (1) the impacting node satisfies the configuration in Figure 6 above and (2) the rotation-translation combination was done uniformly for all impacts.

These variations resulted into 66 simulations set to output d3plots; five thicknesses of both the split and unsplit shells shell impacting two different anvils at three impact locations and an impact to two anvils at all three locations with completely no shell. These models were saved as keyword files in one separate folder for LS-DYNA numerical processing using the LS DYNA Manager solver.

### **2.3 DYNA Processing**

The keyword files were run using the LS DYNA Manager solver in sequence using Matlab automation assigning memory of sixty million to each run. The cumulative run time for all the simulations was about 33 hours but this would vary with respect to the computer processing speed of the workstation used.

### **2.4 Data Post Processing**

#### **2.4.1 Head Injury Potential Assessment: Head Injury Criterion (HIC)**

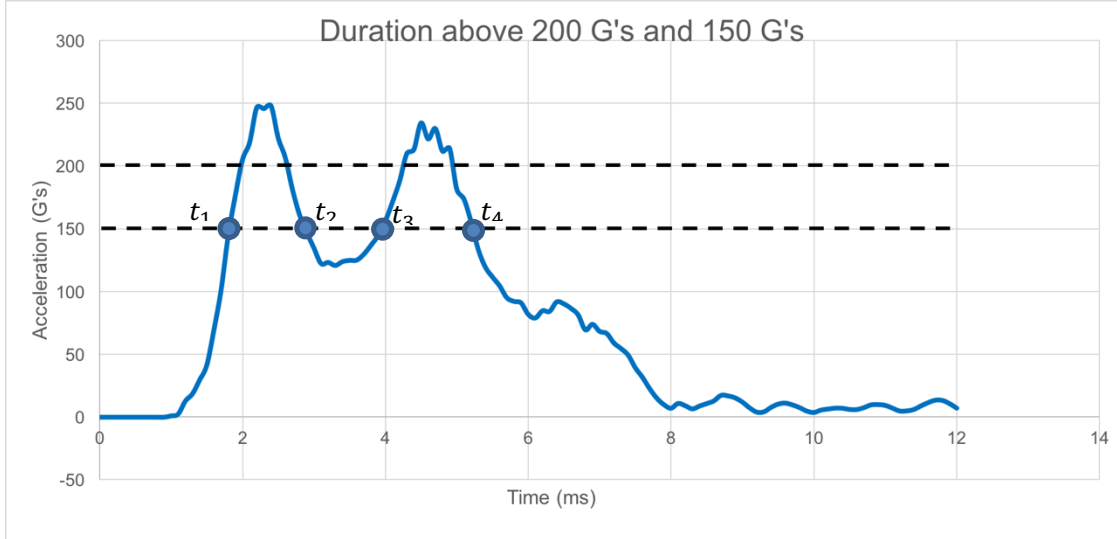
The resulting d3plots were opened in LS PREPOST and the HIC was derived from the acceleration-time plots of the accelerometer in the NCAC Hybrid III head model. Head Injury Criterion (HIC) is a function of acceleration and impact duration shown by Equation 1 below and is used to quantify performance in impact. A lower HIC value signifies better energy absorbing and energy dissipating capabilities of the helmet under the specific test conditions and variations.

$$\text{HIC} = \left[ \frac{\int_{t_1}^{t_2} a dt}{t_2 - t_1} \right]^{2.5} (t_2 - t_1) \quad (1)$$

Historically, the HIC equation was designed to measure the likelihood of a skull fracture when bare human heads strike steel surfaces. Since skull injury occurs at HICs of 1000, HICs greater than 1000 are considered unsafe. However, since liners in helmets absorb impact and increase impact duration, typical HIC values of safe helmets by far exceed the 1000 HIC value threshold. As such, HICs are not used by the American helmet standard to measure helmet performance. Rather, peak accelerations, threshold accelerations and their respective durations are used to quantify performance of motorcycle helmets in the American helmet standard. It requires that (1) peak accelerations do not exceed 400 G's, (2) accelerations above 200 G's do not exceed a cumulative duration of 2 milliseconds, and (3) accelerations above 150 G's do not exceed a cumulative duration of 4 milliseconds.

To determine compliance of the simulations with the European helmet standard which uses HIC to quantify helmet performance, HIC data and peak acceleration data was recorded from LS DYNA generated plots. The cumulative duration the acceleration-time plots of the impacts spent above 200 G's and 150 G's was also calculated as shown below.

## 2.4.2 Measurement of duration above acceleration thresholds: 200 G's and 150 G's.



**Figure 9: Measurement of duration above 200G's and 150G's. In the plot above, a summation of only the duration the plot is above the threshold was calculated since the plot had two peaks.**

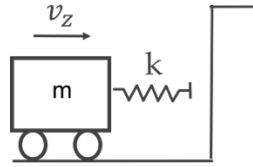
$$\sum \text{time} > \text{Threshold} = \sum (t_{n+1} - t_n) \quad (2)$$

Equation 2 was used to calculate the summation of the duration above the two thresholds, 150 G's and 200 G's, using Matlab to investigate compliance to the American Helmet Standard.

## 2.4.3 Data analysis

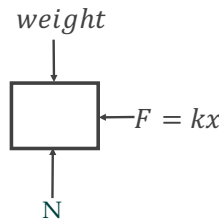
### 2.4.3.1 Understanding the effects of helmet stiffness on acceleration of the helmeted head.

The helmeted impact of a motorcyclist with a head mass of ( $m$ ) was modeled per Figure 10 below. The motorcycle helmet was modeled as a spring with stiffness ( $k$ ) and the cyclist with a velocity ( $v$ ) in the horizontal axis.



**Figure 10: Helmeted Motorcyclist before Impact model.**

Forces in the horizontal axis were resolved for the resulting free body diagram in Figure 11 below to give the differential Equation 3 governing the impact.



**Figure 11: Free Body Diagram of the forces on the head during an impact with a stationary object, where the helmet is modeled with a stiffness, k.**

$$m\ddot{x} + kx = 0 \quad (3)$$

Solving the resulting differential Equation 3 with initial conditions;  $x = 0$  and  $\dot{x} = v_z$ , at  $t = 0$  resulted into Equation 4 for displacement ( $x$ ).

$$x = \frac{v_z}{\sqrt{k/m}} \sin \omega t \quad (4)$$

Double differentiating Equation 4 resulted into Equation 5 below for acceleration of the helmeted head.

$$\ddot{x} = -\left(V_0 \sqrt{k/m}\right) \sin \left(\sqrt{\frac{k}{m}} t\right) \quad (5)$$

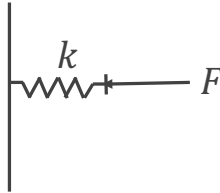
From Equation 5 above, the term just before the sine function is the Peak Acceleration ( $\ddot{x}_{peak}$ ) as shown by Equation 6 below.

$$\ddot{x}_{peak} = \left(V_0 \sqrt{k/m}\right) \quad (6)$$

Equation 6 above for peak acceleration of a helmeted head shows that the square root of helmet stiffness is linearly related to Peak Acceleration of the helmeted head. This relationship was useful in explaining some of the trends that were seen.

#### 2.4.3.2 Understanding the effects of helmet properties on stiffness.

To understand the effects of contact area, material properties and liner thickness on helmet stiffness, it is useful to review the deflection equation for a column in compression. The helmet was modeled as a spring with stiffness  $k$  per Figure 12 below.



**Figure 12: Spring motorcycle helmet model in axial loading.**

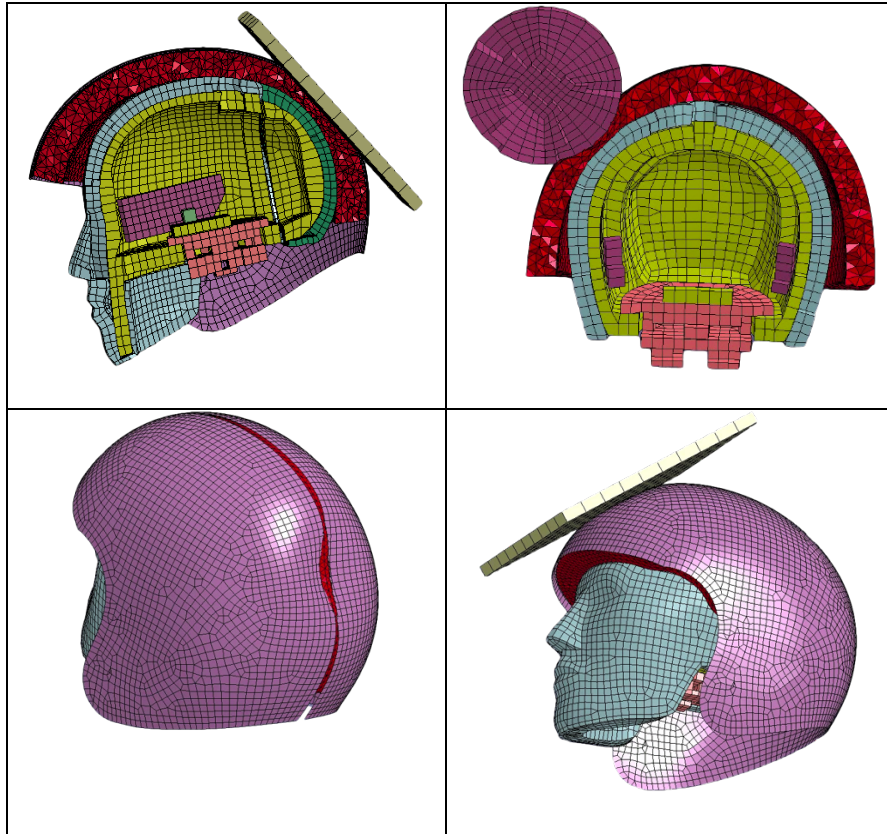
Equation 8 below for helmet stiffness ( $k$ ) of a column in axial loading shows that helmet stiffness is linearly related to the contact area and the material's Young's modulus and inversely related to liner thickness ( $L$ ). Although this is a gross simplification, it was useful in explaining some of the trends that were seen.

$$x = \frac{FL}{AE} \quad (7)$$

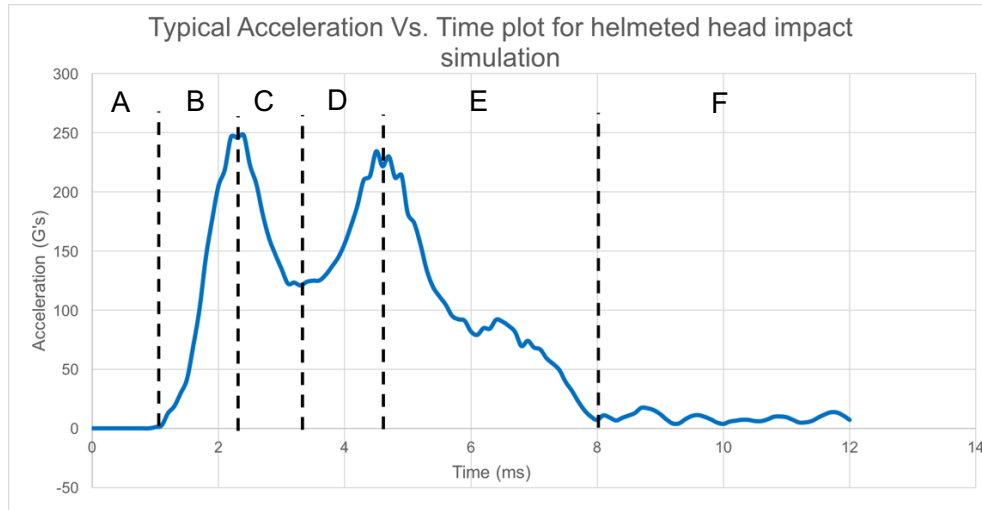
$$k = \frac{AE}{L} \quad (8)$$

Linear regressions relating helmet HIC and Peak Accelerations with increase in shell thickness and variation of continuity were generated using JMP statistical software.

### 3. Results



**Figure 13: Impact Simulation screenshots. Top left: Liner deformation in back impact on flat anvil. Top right: Liner deformation in side impact without the shell. Bottom left: Shell cave-in along split line during back impact to round impact-anvil (blanked). Bottom right: Shell deformation during frontal impact on flat anvil.**



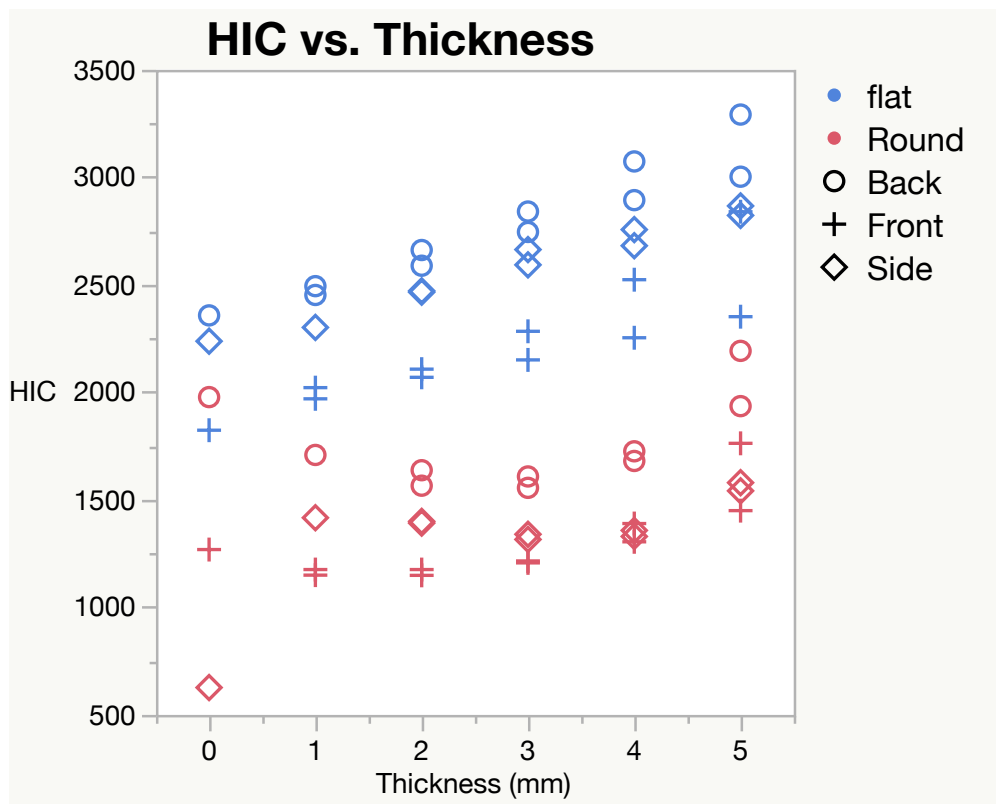
**Figure 14: Typical Acceleration vs. Time plot for a helmeted head impact simulation. In region A, the helmeted head was moving towards the anvil, in B, the helmet contacted the anvil, in C the head impacted the impact-absorbing liner, in D, the deformable shell rebounded energy back to the liner which in turn transmitted it to the head, in E, the head is rebounding away from the liner and in F, the helmeted head was completely airborne.**

### 3.1 Helmet Standards Compliance

**Table 2: Compliance of impact simulations to the European and American Helmet Standards. Apart from back impacts to the round anvil, 100% of impacts to the round anvil were compliant to both the European and American helmet standards. Back Impacts had the lowest compliance in comparison to all other impact locations for both flat anvil and round anvil impacts. Front impacts generally had the highest compliance.**

Anvil	Position	Percentage of simulations that passed the European Standard	Percentage of simulations that passed the American Standard
Flat	Front	24%	12%
	Side	0%	15%
	Back	0%	6%
Round	Front	100%	100%
	Side	100%	100%
	Back	30%	100%

### 3.2 Head Acceleration Criterion (HIC) performance

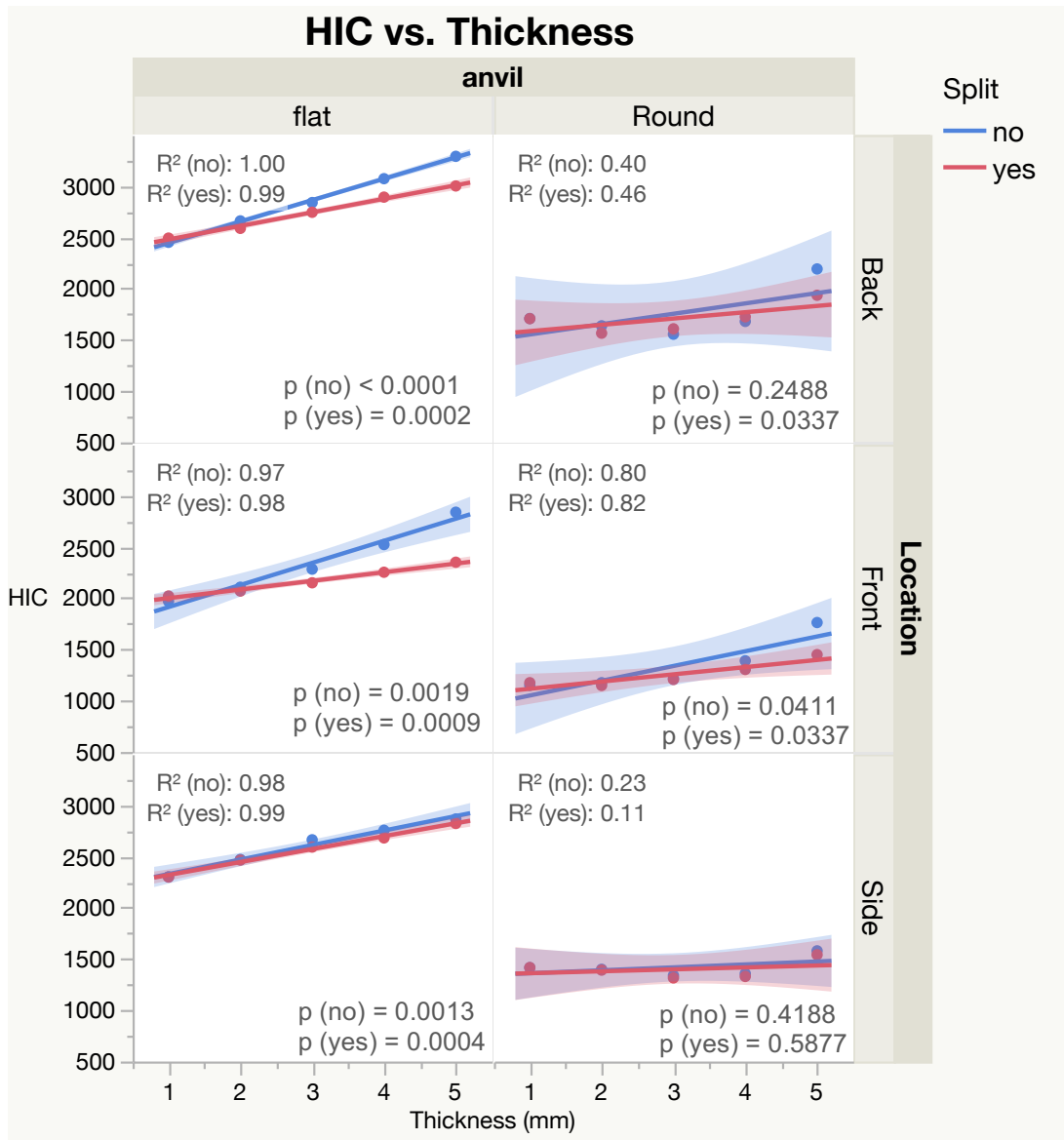


**Figure 15: HIC by thickness, anvil type and impact location for all 66 impacts. The side impact on a round anvil resulted into the lowest HIC while the back impact on a flat anvil resulted into the highest Peak Acceleration. Generally, impacts to the flat anvil resulted in higher HICs than impacts to the round anvil.**

**Table 3: Average Percent Change in HIC after splitting the helmet shell for all impact locations and anvils by shell thickness. Splitting the 1mm thick shell increased HIC by less than 3% while splitting the shell for shell thicknesses greater than 1 mm**

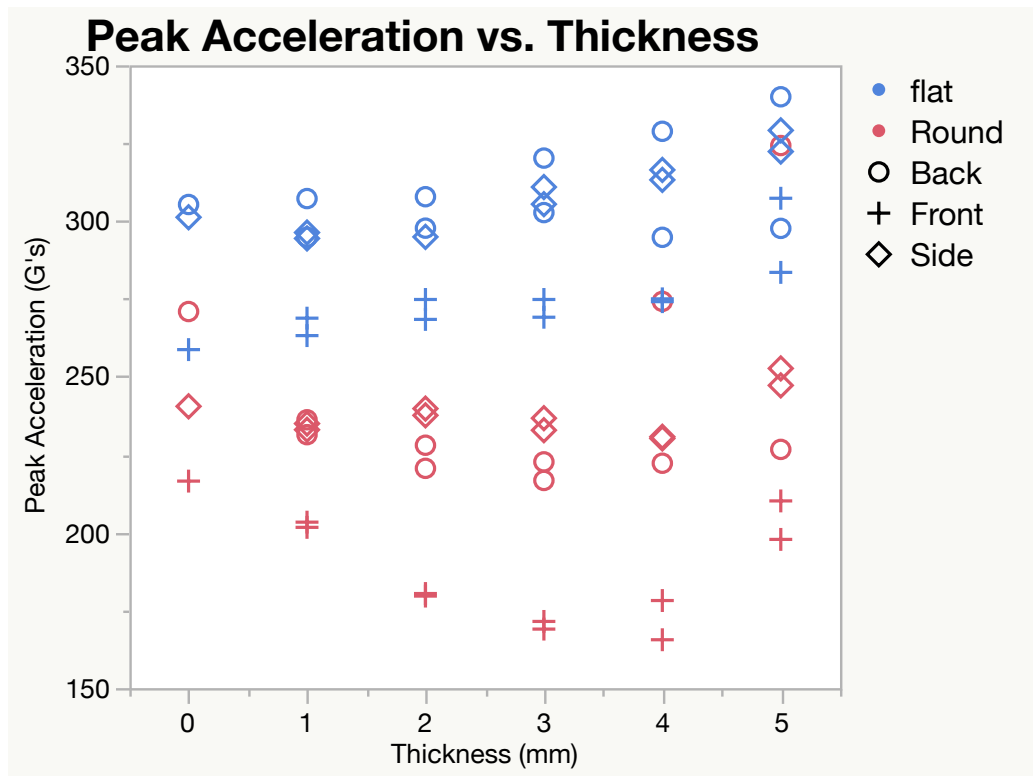
Shell thickness	1 mm	2 mm	3 mm	4 mm	5 mm
Av. % Change in HIC after split. Mean (Standard Deviation)-All impacts combined	+1.1%(1.3)	-2.0%(1.5)	-1.8%(3.1)	-4.1%(4.5)	-9.9%(7.0)





**Figure 16: HIC vs Thickness by impact location, anvil type, and continuity. All HICs for round anvil impacts were lower than HICs for flat anvil impacts. Splitting the shell for 1mm shell thicknesses generally slightly increased HIC while splitting the shell for shell thicknesses greater than 1 mm generally reduced HICs with increase in shell thickness. Splitting the shell generally did not make a difference to HIC performance for side impacts. The linear statistical model more closely models flat anvil impacts than it does round anvil impacts.**

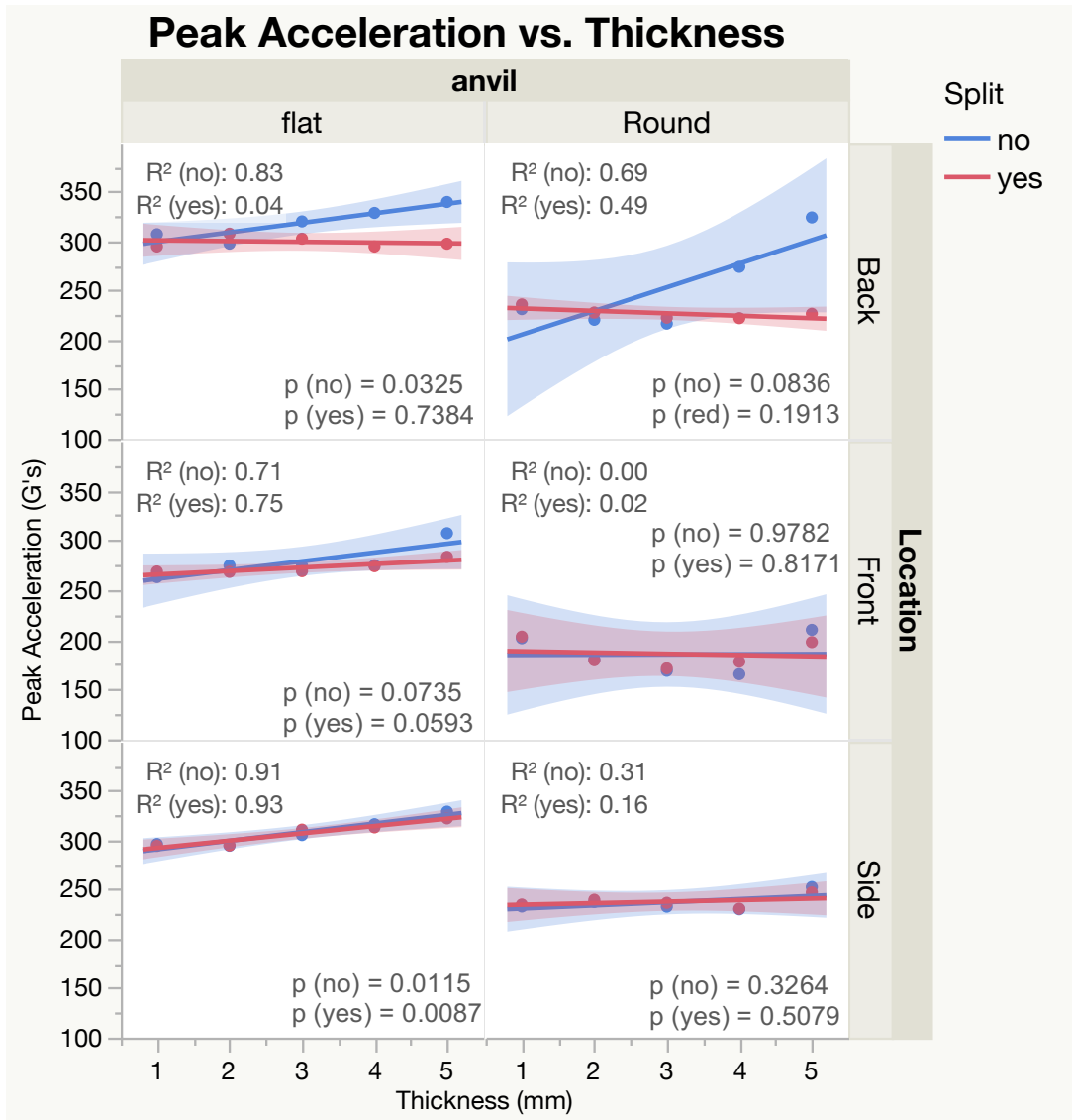
### 3.3 Peak Acceleration performance



**Figure 17: Peak Accelerations by thickness, anvil type and impact location for all 66 impacts. The front impact on a round anvil resulted into the lowest Peak Acceleration while the back impact on a flat anvil resulted into the highest Peak Acceleration. Generally, impacts to the flat anvil resulted in higher Peak Accelerations than impacts to the round anvil.**

**Table 4: Average Percent Change in Peak Accelerations after splitting the helmet shell for all impact locations and anvils vs increase in shell thickness. Splitting both the 1mm and 2mm thick shells increased Peak Accelerations by less than 5% while splitting the shell for shell thicknesses greater than 2 mm generally reduced Peak Accelerations with increase in shell thickness ranging from +5% to -20.6%. (negatives symbolize reductions while positives, increments)**

Shell thickness	1 mm	2 mm	3 mm	4 mm	5 mm
Av. % Change in P.A after split. Mean (Standard Deviation) -All impacts combined	+0.1%(2.3)	+0.5%(2.3)	-0.6%(3.1)	-4.2%(9.2)	-10.1%(10.5)



**Figure 18: Peak Acceleration vs Thickness by impact location and continuity. All Peak Accelerations for round anvil impacts were lower than Peak Accelerations for flat anvil impacts. Splitting the shell for shell thicknesses 1mm and 2mm generally slightly increased Peak Acceleration while splitting the shell for shell thicknesses greater than 2 mm generally reduced Peak Acceleration with increase in thickness. Splitting the shell generally did not make a difference to Peak Acceleration performance for side impacts. The linear statistical model more closely models flat anvil impacts than it does round anvil impacts.**

## 4. Discussion

### 4.1 *Helmet Standards Compliance*

Round anvil impacts had significantly higher compliance to both the European and American standards compared to flat anvil impacts. (Impacts to all locations had 100% compliance to both standards, but back impacts which had 30% compliance for round anvil impacts while compliance for the flat anvil impacts ranged from 0% to 24%). This is the case since all round anvil impacts also resulted into significantly lower HICs and Peak Accelerations than flat anvil impacts. In round impacts, the sphere's surface area engages the helmeted head gradually over a longer duration. A longer impact duration implies lower HICs per the HIC equation. (Equation 1 herein) As such, the difference in geometry of the impact anvils and its significance on impact duration could have significantly contributed to the lower HICs for round anvil impact. Additionally, the incident impact velocity for the round anvil impacts was 0.8 m/s (13%) less than that of flat anvil impacts. Velocity is an integral of acceleration and acceleration is an input of the HIC equation. (Equation 1 herein) As such, the lower incident velocity for round anvil impacts contributed to the generally lower HIC and Peak Accelerations in round anvil impacts.

Compliance to both the European and American standards was highest for front impacts, followed by side impacts and back impacts had the lowest compliance. Liner thickness at the front, side and back impact locations was 24mm, 16 mm and 18mm respectively. According to Equation 8 herein for stiffness of the helmet, increase in liner thickness ( $L$ ) reduces stiffness of the helmet which in turn reduces peak acceleration and HIC. However, this only explains why the front impacts to the thickest liner were the most compliant to the standards. An explanation why back impacts performed

significantly worse than side impacts yet (1) the liner thickness at the back impact-location was 11% thicker than the liner thickness at the side impact location and (2) half of the back impacts were along the split line which improved performance, is still unknown and is an opportunity for further research.

#### **4.2 Head Acceleration Criterion (HIC) performance**

For both round and flat anvil impacts, HIC increased with increase in shell thickness. ( $p < 0.0001$ :  $p = 0.5877$ ) implying that the slope of the line of best fit was always positive. Increase in shell thickness increases stiffness of the shell. Per Equation 5 herein, increase in stiffness increases acceleration which in turn increases HIC values.

Splitting the shell resulted in a slight increase in HIC for the 1mm shell (less than 3%) and a general reduction in HIC for thicknesses greater than 1 mm. (2%: 9.9% HIC average HIC reduction for all impact locations and anvils). Splitting the shell reduces the stiffness of the shell. A decrease in shell stiffness decreases acceleration which in turn decreases HIC. However, splitting the shell did not make a significant difference in HIC performance for side impacts since the side impact is not along a split line hence its close semblance in HIC performance to the unsplit side impact.

#### **4.3 Peak Acceleration performance**

For both round and flat anvil impacts, Peak Acceleration increased with increase in shell thickness. ( $p = 0.0087$ :  $p = 0.9782$ ) implying that the slope of the line of best fit was always positive. Increase in shell thickness increases stiffness of the shell. Per Equation 6 herein, increase in stiffness increases Peak Acceleration.

Splitting the shell resulted in a slight increase in Peak Acceleration for the 1mm and 2mm shells (less than 3% average Peak Acceleration increment for all impact locations and anvils) and a general reduction in Peak Acceleration for thicknesses

greater than 2 mm. (0.6%: 10.1% average Peak Acceleration reduction for all impact locations and anvils). Splitting the shell reduces the stiffness of the shell. A decrease in shell stiffness decreases Peak Acceleration per Equation 6 herein. However, splitting the shell did not make a significant difference in Peak Acceleration performance for side impacts since the side impact is not along a split line hence its close semblance in Peak Acceleration performance to the unsplit side impacts.

## 5. Research Limitations

Based on the linear regression model used, flat anvil impacts have a narrower confidence corridor while round anvil impacts have wide confidence corridor. Per Equation 5 herein, the root of stiffness is directly proportional to acceleration. However, linear regression used assumes a general linear relationship between acceleration and stiffness. As such, modelling the line of best fit to reflect a more accurate relationship between stiffness and acceleration could have resulted into narrower confidence corridors for the round impact anvils to result higher  $R^2$  values.

In this research, a convergence study was not done to find the optimal mesh size that allows satisfactory accuracy of the results with respect to computational expense of the simulation. Given more time, this research would benefit from a convergence study even with the fact that the trends noticed at the current mesh size of 4 mm are expected to be noticed with a finer mesh size.

This study was limited to protection from blunt impact surfaces in which regard, shells are less important. For sharp impact surfaces, having no shell at all or a shell of very low stiffness would expose the head to injury due to penetration of the sharp impact surface.

This study was also limited to only one liner material of one density and one shell material. Increase in shell thickness can be offset by a less stiff liner to maintain performance of the helmet.

## **6. Conclusion**

Increase in shell thickness significantly reduces motorcycle shell performance and splitting the helmet shell does not significantly affect motorcycle helmet performance. These deductions have potential to significantly cut motorcycle helmet costs up to 25% in the Tropics by leveraging economies of scale from reduced shell material use and shipping cost reduction.



## 7. Appendix

**Table 5: Side location Impacts on flat anvil raw data.**

Thickness (mm)	Split?	Time (ms) >150G's	Time (ms) >200G's	P.A (G's)	HIC	Compliant to ECE standard?	Compliant to FMVSS 218 standard?
0	N/A	2.5	1.8	301.2	2238	No	Yes
1	Yes	2.4	1.8	294.4	2300	No	Yes
1	No	2.6	1.8	296.3	2302	No	Yes
2	Yes	3.0	1.8	294.4	2466	No	Yes
2	No	3.1	1.8	294.6	2472	No	Yes
3	Yes	3.0	2.1	310.9	2593	No	No
3	No	3.1	2.2	305.4	2664	No	No
4	Yes	3.0	2.5	313.2	2682	No	No
4	No	3.1	2.6	316.4	2757	No	No
5	Yes	2.9	2.5	322.3	2823	No	No
5	No	3.0	2.5	329.1	2867	No	No

**Table 6: Back location Impacts on flat anvil raw data**

Thickness (mm)	Split?	Time (ms) >150G's	Time (ms) >200G's	P.A (G's)	HIC	Compliant to ECE standard?	Compliant to FMVSS 218 standard?
0	N/A	2.6	2.0	305.3	2358	No	Yes
1	Yes	2.6	2.1	294.8	2494	No	No
1	No	2.8	2.1	307.2	2453	No	No
2	Yes	2.9	2.0	307.8	2589	No	Yes
2	No	3.0	2.3	297.7	2662	No	No
3	Yes	3.1	2.3	302.7	2746	No	No
3	No	3.4	2.4	320.2	2841	No	No
4	Yes	3.0	2.5	294.8	2894	No	No
4	No	3.5	2.2	328.75	3074	No	No
5	Yes	2.9	2.4	297.6	3003	No	No
5	No	3.5	2.6	339.9	3292	No	No

**Table 7: Front location Impacts on flat anvil raw data**

Thickness (mm)	Split?	Time (ms) >150G's	Time (ms) >200G's	P.A (G's)	HIC	Compliant to ECE standard?	Compliant to FMVSS 218 standard?
0	N/A	2.7	1.6	258.7	1824	Yes	Yes
1	Yes	2.8	1.9	268.8	2022	Yes	Yes
1	No	2.8	1.9	263.2	1970	Yes	Yes
2	Yes	2.8	2.0	268.4	2070	Yes	Yes
2	No	2.9	2.1	274.9	2108	Yes	No
3	Yes	2.9	2.1	269.1	2151	Yes	No
3	No	3.0	2.1	274.8	2284	Yes	No
4	Yes	3.0	2.1	274.1	2254	Yes	No
4	No	3.0	2.3	275.0	2524	No	No
5	Yes	2.9	2.1	283.5	2352	No	No
5	No	2.8	2.3	307.3	2840	No	No

**Table 8: Back location Impacts on spherical anvil**

Thickness (mm)	Split?	Time (ms) >150G's	Time (ms) >200G's	P.A (G's)	HIC	Compliant to ECE standard?	Compliant to FMVSS 218 standard?
0	N/A	2.5	1.8	270.9	1978	Yes	Yes
1	Yes	2.7	1.6	236.2	1708	Yes	Yes
1	No	2.5	1.6	231.4	1709	Yes	Yes
2	Yes	2.5	1.1	228.0	1566	Yes	Yes
2	No	3.0	0.9	220.6	1638	Yes	Yes
3	Yes	2.5	0.9	222.7	1609	Yes	Yes
3	No	3.1	0.2	216.7	1556	Yes	Yes
4	Yes	4.0	0.8	222.2	1726	Yes	Yes
4	No	3.2	0.5	274.2	1681	Yes	Yes
5	Yes	1.6	1.0	226.7	1936	Yes	Yes
5	No	4.0	0.8	324.2	2193	No	Yes

**Table 9: Front location Impacts on spherical anvil**

Thickness (mm)	Split?	Time (ms) >150G's	Time (ms) >200G's	P.A (G's)	HIC	Compliant to ECE standard?	Compliant to FMVSS 218 standard?
0	N/A	2.2	0.8	216.5	1269	Yes	Yes
1	Yes	2.3	0	203.3	1176	Yes	Yes
1	No	2.1	0	201.6	1150	Yes	Yes
2	Yes	2.7	0	179.6	1149	Yes	Yes
2	No	2.8	0	180.4	1176	Yes	Yes
3	Yes	3.2	0	171.4	1207	Yes	Yes
3	No	1.1	0	169.0	1216	Yes	Yes
4	Yes	3.3	0	178.1	1305	Yes	Yes
4	No	2.5	0	165.5	1390	Yes	Yes
5	Yes	2.8	0	197.8	1450	Yes	Yes
5	No	2.8	0.4	210.1	1763	Yes	Yes

**Table 10: Side location Impacts on spherical anvil**

Thickness (mm)	Split?	Time (ms) >150G's	Time (ms) >200G's	P.A (G's)	HIC	Compliant to ECE standard?	Compliant to FMVSS 218 standard?
0*	N/A	1.1	0.5	240.5	627.2	Yes	Yes
1	Yes	2.2	1.2	235.0	1417	Yes	Yes
1	No	2.2	1.2	233.0	1416	Yes	Yes
2	Yes	2.0	1.1	239.8	1392	Yes	Yes
2	No	2.0	1.1	237.6	1400	Yes	Yes
3	Yes	2.1	0.8	236.7	1316	Yes	Yes
3	No	2.6	0.8	232.8	1340	Yes	Yes
4	Yes	2.2	0.7	230.7	1330	Yes	Yes
4	No	2.6	0.8	230.2	1358	Yes	Yes
5	Yes	2.3	1.2	247.2	1542	Yes	Yes
5	No	2.3	1.4	252.7	1580	Yes	Yes

\*CONTACT\_AUTOMATIC\_SURFACE\_TO\_SURFACE\_ID

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$# cid title
1Shell to Flat Anvil
$# ssid msid sstyp mstyp sboxid mboxid spr mpr
1000000 5000000 3 3 0 0 0 0
$# fs fd dc vc vdc penchk bt dt
0.30000001 0.2 0.0 0.0 0.0 0 0.01.00000E20
$# sfs sfm sst mst sfst sfmt fsf vsf
1.0 1.0 0.0 0.0 1.0 1.0 1.0 1.0
```

\*CONTACT\_AUTOMATIC\_SURFACE\_TO\_SURFACE\_ID

```
$# cid title
2Liner to Shell
$# ssid msid sstyp mstyp sboxid mboxid spr mpr
4000000 1000000 3 3 0 0 0 0
$# fs fd dc vc vdc penchk bt dt
0.30000001 0.2 0.0 0.0 0.0 0 0.01.00000E20
$# sfs sfm sst mst sfst sfmt fsf vsf
1.0 1.0 0.0 2.0 1.0 1.0 1.0 1.0
```

\*CONTACT\_TIED\_NODES\_TO\_SURFACE\_OFFSET\_ID

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$# cid title
3R Pad to Shell
$# ssid msid sstyp mstyp sboxid mboxid spr mpr
2000000 1000000 4 3 0 0 0 0
$# fs fd dc vc vdc penchk bt dt
0.0 0.0 0.0 0.0 0.0 0 0.01.00000E20
$# sfs sfm sst mst sfst sfmt fsf vsf
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```

\*SET\_NODE\_LIST\_TITLE

R Ear Glue

```

$#  sid  da1  da2  da3  da4  solver
2000000  0.0  0.0  0.0  0.0  0.0MECH

$#  nid1  nid2  nid3  nid4  nid5  nid6  nid7  nid8
0  0  0  0  0  0  0  0

*CONTACT_TIED_NODES_TO_SURFACE_OFFSET_ID

$#  cid  title
4L Pad to Shell

$#  ssid  msid  sstyp  mstyp  sboxid  mboxid  spr  mpr
3000000  1000000  4  3  0  0  0  0

$#  fs  fd  dc  vc  vdc  penchk  bt  dt
0.0  0.0  0.0  0.0  0.0  0  0.01.00000E20

$#  sfs  sfm  sst  mst  sfst  sfmt  fsf  vsf
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*SET_NODE_LIST_TITLE

L Ear Glue

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$#  nid1  nid2  nid3  nid4  nid5  nid6  nid7  nid8
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*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_ID

$#  cid  title
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$#  fs  fd  dc  vc  vdc  penchk  bt  dt
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$#  sfs  sfm  sst  mst  sfst  sfmt  fsf  vsf
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*CONTACT_AUTOMATIC_SURFACE_TO_SURFACE_ID

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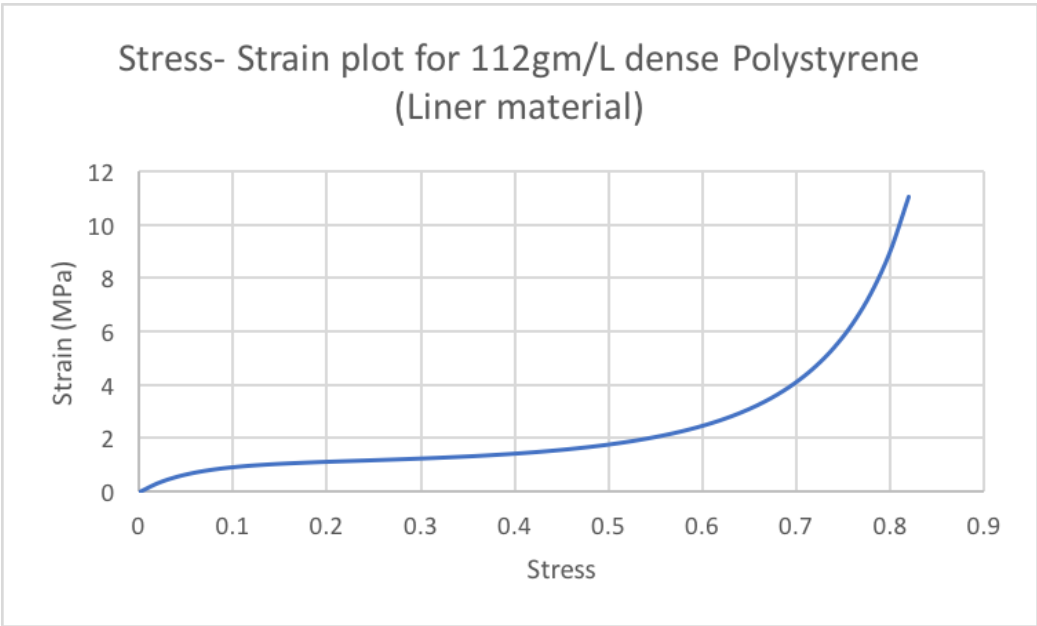


```

$# cid title
6Skullcap Skin to Liner
$# ssid msid sstyp mstyp sboxid mboxid spr mpr
59100012 4000000 3 3 0 0 0 0
$# fs fd dc vc vdc penchk bt dt
0.30000001 0.2 0.0 0.0 0.0 0 0.01.00000E20
$# sfs sfm sst mst sfst sfmt fsf vsf
1.0 1.0 0.0 0.0 1.0 1.0 1.0 1.0

```

**Figure 19: LS DYNA Contact definition card**



**Figure 20: Loading curve for 112mg/L dense polystyrene liner material.**

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