Nature-Inspired Biomechanical Helmet for Enhanced Head Injury Prevention

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AUTHOR'S DECLARATION

I, Hafiz Muhammad Yasir Bhatti hereby state that my MS thesis titled "Nature-Inspired Biomechanical Helmet for Enhanced Head Injury Prevention" is my own work and has not been submitted previously by me for taking any degree from the National University of Sciences and Technology, Islamabad or anywhere else in the country/ world.

At any time if my statement is found to be incorrect even after I graduate, the university has the right to withdraw my MS degree.

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Date: 28-8-2024

DEDICATION

“I dedicate this thesis to my parents and my sisters, whose unwavering love, encouragement, and sacrifices have been my greatest motivation. Their belief in me has been the foundation of my academic journey. To my supervisor, Dr Zartasha Mustansar, whose insightful guidance, patience, and expertise have been instrumental in shaping this research. Your support has been invaluable for me. I also want to thank my friends at National University of Science and Technology, Islamabad especially Engr. Abdul Rehman Ahmed, Engr. Bilal Sarwar, and Engr Arqam Habib Khan, whose worth mentioning, and constant support have provided the perfect balance to the rigors of academic life and co-curricular activities. Lastly, I extend my gratitude to the School of Interdisciplinary Sciences and Engineering (SINES) at National University of Sciences and Technology, Islamabad, for providing a stimulating and supportive environment that has fostered my intellectual growth and academic growth.”

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ABSTRACT

Head injuries are prevalent outcomes of accidents and can result in severe, life-altering conditions, including brain damage and cognitive impairment. Helmets play a crucial role in reducing the risk of head trauma by absorbing impact forces and protecting the skull. This study focuses on the material and design aspects of nature-inspired helmet to analyze head impacts using the Finite Element Method (FEM). The primary objective is to employ finite element analysis (FEA) to model head impacts and evaluate stress patterns on the human head when protected by a mechanically enhanced helmet. The research aims to establish the differences in impact responses between a proposed helmet, conventional helmet and headform model.

As of methodology properties of organic structures that are known to possess hyper-elasticity, high degrees of tensile strength and the ability to absorb shock has been utilized. By drawing inspiration from the human spinal column, renowned for its compressive load-bearing capacity, and the woodpecker's skull, the helmet design utilized in this study is both novel and unique. In this research, these organic characteristics are compared with the classical synthetic helmet materials in the hope of finding better candidates that may enhance the protection mechanism. This leads to incorporating advanced materials and biomechanical research methods to evaluate the effectiveness of these materials in realistic stress tests that mimic impacts observed in real-time life conditions.

The findings of this research could lead to significant advancements in helmet design through the integration of bio-inspired materials and analysis, ultimately reducing head injuries in sports, transportation, and other fields prone to such trauma.

Keywords: Finite element analysis (FEA), human head, helmet, biomechanics, material properties, impact stress, bio-inspired materials, helmet design, head injuries, sports, trauma.

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LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

- Traumatic Brain Injuries (TBI)
- Finite Element Analysis (FEA)
- Finite Element Method (FEM)
- Multi-directional Impact Protection System (MIPS)
- Diffuse axonal injury (DAI)

Chapter No.1

1 Introduction

Investigating head injuries, especially in the context of sports and transportation, safety is a crucial field because of the significant impact these injuries can lead to individuals. Helmets' main functions are to provide protection; however, their efficacy is primarily contingent upon the materials and design employed. Advancements in the fields of materials science and biomechanics have recently opened new possibilities for improving the performance of helmets. The aim of this research is to employ and implement the novelty by using finite element analysis (FEA) in simulating head traumas or head injuries in a unique manner.

The goal is to contrast the apportioning of stress affecting the human head if it is protected by a helmet and if it is not. Finite element analysis (FEA) is one of the most efficient computational methods that facilitate appropriate modeling of real-life occurrences, for instance, the mechanical behavior of materials under impact environment. This technology has therefore applied in the analysis of Traumatic Brain Injuries (TBI) and in the development of protective helmets. Chen et al. (2023) designed a new helmet combining helmet and elements from biology. This design has auxetic lattice liners that incorporates negative poison ratio, and results have revealed that it offers better protection reducing the head injuries to a lesser level as compared to other helmet designs [1].

The mechanics of natural/biological materials and the biomechanics of the woodpecker's skull [2] and human spine [3] that are notable for their resilience and ability to withstand and deal with stress and pressure of impacts. The skull of a woodpecker for example has evolved in such a unique way that it is able to sustain the forceful and repetitive beating on trees without getting injured. This makes it a perfect prototype for the creation of helmets inspired by biological mechanisms. However, similarly inspired by woodpecker's skull, this study takes into account helmets that can be modeled using the human spine inspiration. The thesis aims at creating better models that might improve protection by incorporating biomechanical attributes into the synthetic helmets' material.

The methodology includes simulation based on actual accident scenarios to confirm the results to increase credibility as an example of the feasibility study. Some of the mentioned materials were subjected to computer simulations studies to determine their protection levels concerning actual impact situations in the future. In this case, stress is applied to different materials and by this it is possible to gain a better understanding of the behavior of these helmets which helps in developing new but better helmets.

Moreover, active and incorporated new material like hyper-elastic rubbers which has good response towards impact loads also showed promising results in recent research. These materials have better ability to absorb and dissipate impact energy and contacts therefore reducing the chances of head injury[1].

From this research, the design of helmets may be revolutionized by setting up full complex and complete simulations using natural materials from nature. Keeping the goal aligned that is to reduce the severity of incidence of head injuries in various risky activities the quality of community health and safety can be largely enhanced for bikers and other individuals in sports and stunt activities [4].

1.1 Significance of the study

Prevention of head and brain injuries is important for several different reasons. Mainly, head injury can result in severe and permanent consequences which include cognitive disabilities like concussion, physical disability, and psychological wounds. The expense implicated in the management of brain injuries and the subsequent care required by the individuals is very high and, in many cases, patients involved in the accidents died within a short time. In addition, advances in protective clothing particularly for cycling, motorcycling, dangerous industrial work and contact sports, featuring high-risk activities, have boosted the call for top rated protective apparel and head gears[5].

Using advanced helmets materials and design constructions not only protects the individual's life, but also contributes to a further reduction in the frequency and severity of head injuries to the overall population. Thus, this can help decrease mortalities, healthcare costs, improve quality of life and increase participation in physical activities through eradicating the safety concerns. Therefore, progress in helmet development is closely linked to broader impacts beyond the protection of individual users. The research therefore contributes to help make better and safer helmets that can greatly reduce the chances of head injury in diverse risky activities and operations.

1.2 Motivation Behind the Study

The primary inspiration comes from nature's ability to develop superior resilience through environmental challenges and the principle of survival of the fittest. This work is similarly motivated by nature, aiming to reduce cranial injuries across various domains, including sports, transportation, industrial, and recreational activities.

1.3 Problem Statement

There are different kinds of helmets that had been designed and manufactured using different materials in the past but still there is need for improvement in helmets. Now the question arises how can we improve helmet safety and comfort using nature-inspired biomechanics and sustainable materials for head injury prevention?

1.4 Objectives of the Study

The aims and objectives of this research are therefore to explore and develop natural inspired helmets which enhance head protective features in a convincing and permanent manner. The aim of the research is as follows.

1. To develop a computational model for bio-inspired helmets.

2. To carry out the impact analysis for helmets comprising of different materials using FEA.

3. To compare the developed bio-inspired helmet with conventional helmets using FEA.

1.5 Expected Outcomes

Helmet design can be significantly enhanced by integrating bio-inspired materials that mimic the structural and functional properties of woodpecker skulls and human spines. These natural materials provide remarkable resistance to impact and durability, qualities that can be replicated in synthetic counterparts to enhance helmet performance. The researchers presently focus on incorporating these bio-inspired materials into helmet designs to achieve superior energy absorption, enhanced impact resistance, and increased stability against environmental degradation, surpassing the capabilities of traditional materials.[3].

Ultimately, traditional bike helmet materials have offered a reliable and economical basis for safeguarding the users head, the continuous investigation into bio-inspired materials and sophisticated biomechanical analysis methods has the capacity to completely transform helmet designs. These advancements have the potential to result in helmets that are safer and more efficient, leading to a considerable decrease in the occurrence and seriousness of head injuries during high-risk activities.

1.6 Relevance to National Needs

The analysis shows that the need to develop a helmet based on the concept of nature to upgrade the protection of the head from possible brain trauma is not only about survival and personal identity but also has significant implications for nations' guidelines. The research directly aids different national contexts, including public health, economic stability, innovation, and safety in high-risk activities by emphasizing this significant subject.

1.7 Thesis Outline

Every section and chapter of this thesis has been developed to the finest detail to provide an extensive approach toward designing a helmet based on nature to enhance the protection of the head from injuries. The material is divided into numerous highly relevant segments, which focus on separate aspects of the research methodology and the outcomes.

The previously described **Introduction** section reintroduces the study context and establishes the research motives based on the necessity of minimizing head injury rates among bikers, players, and site workers etc. The following section avails the reader of a clear understanding of what is being discussed, as well as the rationale motives for conducting the research.

The second chapter is **Literature Review** analyses for helmet design and advanced helmet material with focus on the existing literature available. Thus, the given text covers the current state of head injury prevention, traditional helmet solutions, and the notion of biomimetic design. This review defines the gaps in knowledge that can be discerned from the past literature, which forms the premise for the novel approaches explored in this thesis.

The third chapter is **Methodology** section explains the means used to assess the effectiveness of the new helmets' designs. The text tells the flow of how to select materials, set up FEA simulations and define the impact test parameters. It is the section that also explains the testing processes for drops or impact tests to simulate results based on different materials and impact condition.

The second last chapter **Results and Discussion** section on the other hand gives detailed of the findings gotten from, the simulation investigation. To assess the performance of the bio inspired helmets against the conventional helmets by bringing out stress distribution. Such outcomes are discussed in the context of the advantages and potential risks of new designs of the island and its main structures.

The last chapter of the thesis is entitled "**Conclusion and Future Work**" in which the leads to the major findings of the thesis, the research contributions to helmet design and head injury mitigation, and the outlines of the foreseeable future research in the given field are outlined.

The **References** section offers a comprehensive list of all the sources used in the thesis, thus ensuring proper citation and allowing the reader to study the subject in further detail.

Chapter No 2

2 Literature Review

The structure of this thesis is designed to reflect the progressive stages of this research, aligning with the objectives that guide to develop a computational model for bio-inspired helmets, carry out the impact analysis for helmets comprising of different materials using FEA, and compare the developed bio-inspired helmet with conventional helmets using FEA to prevent head injuries and its consequences. Initially, this research focuses on analyzing the materials and designs options inspired by nature. This foundational analysis is crucial for understanding the scope of the study with some already existing solutions. Moving forward, research dives into the phase pivotal for conceptualizing a framework that addresses or identifies challenges in traumatic brain injury cases. Each of these sections is self-contained, with a literature review, methodology, and results, allowing a deeper understanding of the specific contributions to the overarching goal and outcomes.

2.1 Bio-Inspired Designs and Materials

Biomimicry or bio-inspired designs are meant to be copying either design or material properties from natural phenomenon or naturally existing life to solve some of the critical issues faced by mankind. In the case of helmet design, biomimicry is based on the concepts of biological engineering, which originates from the study of natural structures and systems with the aim of improving the structures' performance, especially regarding energy absorption and impact resistance components.

More specifically, the skull of the woodpecker has been investigated intensively on account of its capacity to prevent the bird's brain from being damaged even though it experiences steady impacts a frequency on its head. Some of the adaptations are the bones are mostly spongy, the hyoid bone is longer than in other animals and is used to reduce forces, and the beak structure helps in reducing forces[6]. These characteristics have led to the creation of helmet structures that can assimilate force impacts in the same way the woodpecker does.

Nacre, or mother-of-pearl, is also a highly tough and strong material although it is made up of relatively weak components. That is why its hierarchical ''brick-and-mortar' architecture comprised of aragonite platelets and organic matrix layers and able to dissipate the energy and stop the crack propagation. Liu et al. employed the fabrication of nacre-mimetic hierarchical composites for helmets to improve the impact energy absorption capabilities.

The hexagonal pattern of cells in the beehives' combs is credited with excellent strength-to-weight ratio and minimum need for material. These structures have been incorporated in the designing of helmets to afford the user lightweight, powerful impact shields. Hexagonal cells are found to be effective in the distribution of loading forces since their design disperses impact forces evenly. Designs such as these have been put into the making of enhanced helmet liners[5].

Other than that quill of porcupine or hedgehog is composed of outer hard surface and softer inner, and more elastic core. This gives both stiffness and certain freedom for quills to receive and discharge energy produced in the process. The quills of the porcupine have also been used by researchers in finding biomaterials that have its similar characteristics to be used in developing enhanced protective equipment[7]. In some designs they have also shown auxetic properties [1].

The structure of armor is divided into segments in armadillos, which is effective in protecting them and is also mobile. Both segments of the body can contract or expand to enable its occupant against predators or unfavorable environmental conditions. This principle has been used to design helmet shells with segments to be able to offer the required protection while at the same time be flexible[8].

In fishes, scales that have been mined are layered but notwithstanding, they are at the same time both tough and flexible, especially those of costly fishlike predators. These scales' positions are interconnected to offer protection and at the same time enable certain mobility; therefore, they are a model of creating protective and versatile material sets[9]. Helmets with fish scale designs can help increase the impact absorption capability and comfort of the helmet.

However, the human spine can be considered a perfect example of a structure for the bio-inspired concept because it is strong and at the same time has a rather complicated structure with appropriate shock amortization. Another feature of the construction of the spine is inter vertebral disc (IVD) having hyper-elastic properties that assist in absorbing impact forces, thus minimizing the possibilities of getting fractures and other injuries. Revolutionary understanding of the biomechanics of the human spine can help in the designing of better helmets that provide the same kind of protection. [10] [3].

2.2 Conventional Helmet

Helmets are one of the most important pieces of Personal Protective Equipment which are envisaged to reduce the possibilities of head injuries while cycling, mining, motor cycling, sports, etc. Long time many changes have been observed in helmets and materials used; however, many limitations are still present, which continue research processes.

Foam is the preferred material used in helmet liners; specifically, Expanded Polystyrene (EPS) foam. EPS is light in weight, economical and has the advantage of deforming under impact and thus, reducing the amount by which energy is transferred from the impacting force to the skull. However, EPS foam is only good for once-application, single impact protection, that after it has been deformed it has to be disposed of[11][12]. However, EPS has drawbacks that are linked to the questions of multi-impact resistance and flexibility but saving life is more important to buy a new helmet.

Mostly, the exterior of most helmets incorporates a cover formed from Acrylonitrile Butadiene Styrene (ABS), a sort of thermoplastic polymer regarded for its mechanical strength and resilience to influence. The most significant benefit of possessing ABS shells is that it gives them a strong exterior that can be used to absorb the shock with impact forces being spread evenly to a particular region. This also goes a long way in further safeguarding the EPS liner and in turn increases the helmet's overall life span[13]. But it is for a longer period, ABS turns brittle, when the helmet exposed to UV light affects the shield of the ABS material. Current advancements in production have enabled manufacturers to include composite materials in the production of helmets. Composites are products that are made of two or more materials in a manner that one material capitalizes on the other. For example, carbon fiber composites are applied because of high strength per unit weight; thus, they give solid protection while not weighing much, making the helmets not heavy. Other advanced helmets such as high-performance race wear Kevlar, which are aramid fibers, are also utilized for their high impact strength and durability[14].

Figure 1: ABS (blue), PLA (red), and Kevlar-reinforced Onyx (black) parts struck with a hammer

2.3 Advances in Helmet Technology

The enhancement in helmet technology can be said to have transformed in the past few decades mainly because of the desire to improve head protection and minimize the chance of injuring by TBIs. These advancements include several developments in the fabric used, the structure in question, and the techniques of engineering. This section analyses some of the improvements that have been made in helmet technology to enhance safety and performance.

MIPS or Multi-directional Impact Protection System is perhaps one of the biggest innovations in helmets. MIPS adds a smooth inner layer to the helmet that enables the head to slightly glide with regards to the helmet upon an impact. This movement assists in cutting down on the instances of rotational forces that are considered to lead to causes of brain injuries. A study on helmets with MIPS indicated that such helmets were substantially safer than the common ones in minimizing rotational head and brain injuries[15][16]. The toughness and durability of helmets were improved through technology incorporating materials like carbon fiber and Kevlar and still are light in weight. Carbon fiber composites offer a significant strength to weight ratio which is important for offer protection as well as low weight. Kevlar is another aramid fiber with great impact strength and is applied to manufacturing high-performance sports, military and policemen helmets[14]. Elastomeric materials and honeycomb structures are profound innovations in energy management and the lessening of impact. This is because elastomeric materials are the materials that can sustain several impacts and yet they do not undergo any form of permanent deformation and hence, are very useful in industrial applications where strength is very much required. Natural cellular structures such as honeycomb that mimic the regular patterns create excellent energy absorption and distribution properties. Adams et al. explained the possibility using the elastomeric pre-buckled honeycomb structures in the helmet liners with considerable enhancement in the impact attenuation[5]. Another relatively new concept studied in helmet construction is auxetic materials with negative Poisson's ratio. Stretched to the limit, such materials increase only in width that is in the direction of the applied force and therefore afford maximum energy consumption and shock resistance. Chen et al looked at auxetic lattice liners' application in helmets with prediction that such a liner would considerably decrease heads' injury criteria than more conventional composites[1]. Electronic fittings and sensors are added in smart helmets for safety and operational benefits. They can measure g-forces, sense a crash, and even call assistance. Smart helmets come with GPS, cameras, and Bluetooth functions to offer various features such as directions. The literature also shows that smart helmets are a potential solution for enhancing safety while offering immediate data concerning people's conditions in case of an accident[17]. Ventilation systems have been incorporated in helmets to- make the helmets more comfortable and to prevent the helmets from trapping heat. Sophisticated air vents and front grills provide proper ventilation and enable the adjustments of the front mini vents for the right air flow. These systems are special in sports and activities where helmets are used for more than a few hours[18]. An excellent example of this design is the modular helmets whereby the helmet configuration can be changed to meet the user's requirements. For example, there are types of helmets that can easily be turned from a full-face helmet to an open face helmet and vice versa through addition or taking off some parts. Due to this flexibility, modular helmets are widely used among the motorcyclists and adventurer's sports lover[19]. With the innovation of helmets, fit and ergonomic aspects are seen to have recording leaps; not only are helmets more comfortable to wear, but the safety consideration also gets a boost. Today the protection of the head is further enhanced by such features as padding modifications, retention systems and technologies for fit adjustment. A better match not only feels more comfortable but also the helmet that is snug in all the areas stays in the correct position during an impact[20]. There are new viscoelastic multi density foams that enhance energy management and distribution. These foams can even come in different settings of impacts which makes them a better shield against both high and low impacts. In this research, it was revealed that multi-density foams would sufficiently help in the prevention of both skull fracture and intracranial injury[21].

2.4 Head Injuries and its Consequences

Head injuries, especially TBI, constitute a major public health problem in many countries around the world. These injuries could be contact, ballistic, sports, accidents in transport, falls, and even acts of violence. Found out that head injuries imposed on persons and communities are significant and touching the medical, financial, and social aspects.

It is well known fact that head injuries are major killers and incapacitating disorders globally. TBIs account for roughly 40 percent to 45 percent of total injury-related deaths in Pakistan[22]. Next, worldwide it is considered that about 69 million people experience TBI annually[23]. TBIs occur differently in various regions, age brackets, and gender; the most affected brigades include the male Gender and the young adults[24]. Head injuries can range from mild to severe, with TBIs being classified into three primary categories: It can be divided into three major groups, namely, mild, moderate, and severe[25]. The five moderate TBI and coma cases in this study all survived and, for the most part, resumed normal func- tional levels in important daily activities one year post-injury, but they exhibited some tendency to have headache, dizziness, and confusion. The effects of moderate and severe TBIs include, Prolonged coma, New-onset or worsening cognitive disabilities, Motor dysfunction and possible death[26]. The pathophysiology of TBIs involves primary and secondary injury mechanisms. Primary injuries occur now of impact and include concussions, lacerations, and diffuse axonal injury (DAI)[27]. Secondary injuries develop over time and involve processes such as cerebral edema, ischemia, and inflammation, which can exacerbate the initial damage[28]. The clinical outcomes of head injuries are very diverse. Regarding cognitive consequences of TBIs, there are many areas that are affected, and they include memory, attention, and executive function[29]. Motor dysfunction is defined as the loss or reduction in gross motor movements, sensory deficits are any reduction in an individual's ability to perceive touch, pressure, pain, vibration, and/or temperature, and balance issues can be characterized as an inability to maintain an upright position in space[30]. Depression, anxiety and PTSD also occurs in TBI survivors[31]. These TBIs are costly for economies in terms of healthcare, productivity losssiveness of their assets and social welfare. In America alone, the measureable direct and indirect costs of TBIs every year are believed to go beyond $76.5 billion[32]. Such costs include; The medical costs, reestablishment costs , costs due to lost production, and the costs of long term care. TBIs also have social consequences for both the person who gets the injury and society as it includes families of the affected persons. Culturally diverse formal carers experience high levels of emotional and financial pressures while, to the society, they present a loss of productivity and a higher utilization of care services[33]. Measures for discouraging people from sustaining head injuries have been based on public health, legislation and innovation. Prevention drives need to sensify the public on dangers of the causal factors and to encourage safety measures like helmets and seat belts among others[34]. Protection covering laws in holidays like sporting activities and motor cycling help in reducing the occurrence of head injuries[35]. Head protection is an important safeguard against head traumas and one of them is a helmet. They are also intended to attenuate acceleration forces and distribute this force across a larger area thus minimizing transmitted force to the head/Skull/brain[11][12]. Research have confirmed helmet effectiveness in greatly decreasing the instances of head injuries among bikers, motorcyclists, and athletes [36][19]. However, Helmets have limitations basing on the shape, form, and materials that are used in constructing these helmets[37].

2.5 Proposed Study

Based on the literature review the study aims to demonstrate whether bio-inspired helmets can offer superior protection compared to conventional helmets. Metrics for success include lower peak stress values, better energy dissipation, and less deformation during impact tests. Bio-inspired designs are hypothesized to outperform traditional designs, especially in scenarios involving multiple impacts and dynamic loading conditions. This comparison is critical in advancing helmet technology, especially in contexts where head injuries are a significant risk, such as in sports, motorcycle riding, and industrial workspaces. The results could influence future helmet design standards and contribute to enhanced safety measures.

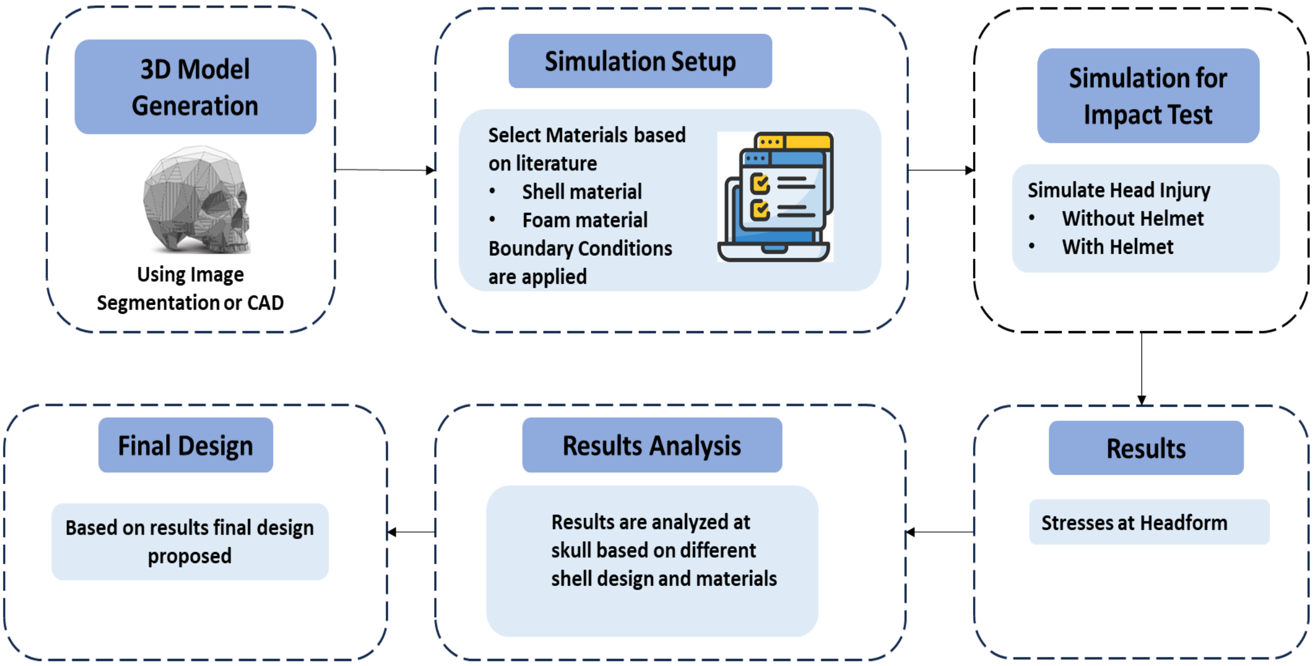
2.6 Summary of the chapter

Conventional helmets typically utilize materials like EPS foam and ABS plastic, which have limitations in multi-impact resistance and durability. Innovations in materials like carbon fiber and Kevlar have improved durability and weight efficiency, but bio-inspired designs drawing inspiration from natural structures like spine, woodpecker skulls and nacre offer potentially superior energy absorption and impact distribution properties.

Chapter No. 3

3 Methodology

The methodology for this research is designed to systematically evaluate and compare the effectiveness of bio-inspired helmet designs against conventional helmets in mitigating impact forces. The overarching goal is to determine which helmet design provides superior protection against head injuries, utilizing Finite Element Analysis (FEA) as the primary tool for simulation and analysis. This section outlines the detailed steps and procedures involved in setting up, executing, and analyzing simulations to assess the mechanical behavior and protective performance of each helmet type under various impact conditions.



3.2 Human Head reconstruction Using Image Processing

The initial procedure in the methodology included combining different anatomical parts of human head types through image segmentation to create a human head model. Image segmentation techniques is a very important process in medical imaging that divides an image into meaningful regions that are likely to represent different structures. In this case, we used MRI scans and CT scans of high-resolution images to gather detailed information on the human head to build the model. MRI and CT scans of the human head with higher resolution were taken. Most of these scans can produce excellent cross-sectional pictures of the head such as the brain, skull, and other head soft tissues like gray matter, white matter, etc.

With regards to image acquisition, the obtained images were enhanced for contrast and the removal of noise for this purpose extra region is cropped down and some filters are applied to visualize features more and more. This step helps in determining the true edges of different anatomical structures that would help in efficient segmentation. As for making assembly geometry, which will be used in our Simulations as it requires precision and no overlapping. Post processing was done on the images as follows: thresholding, region growing, and edge

detection image segmentation techniques were used. These algorithms furnished the automatic demarcation of the different structures in the head like Skull, CSF, Brain, etc. This was done by tools like 3dSlicer or Mimics Materialise to do the segmentation specifically at areas that are our main FEA part to segment in our case the skin, skull and brain have been segmented to make a stereo lithography model (stl) model of human head. After obtaining the segmented 2D images from three different views or perspectives, a life size 3D model was developed with the help of 3d-Slicer software. This model indeed displayed the features of a human head and thus served as a sound model for Finite Element analysis to be made and further impact analysis will be done using FEA tools like Abaqus or ANSYS etc.
After stacking multiple layers of these segmented layers and stitching, a 3d Human head model is reconstructed which is further post processed using CAD to smoothen the surfaces or to remove unnecessary parts from the model. Also, the verification of the model made by 3dSlicer is validated by dimensioning it with real time skull anatomy using literature or with some 3D anatomy tools like VOKA anatomy and it was checked whether the structures segmented by the semi-automated tool corresponded with the real human anatomy or not.

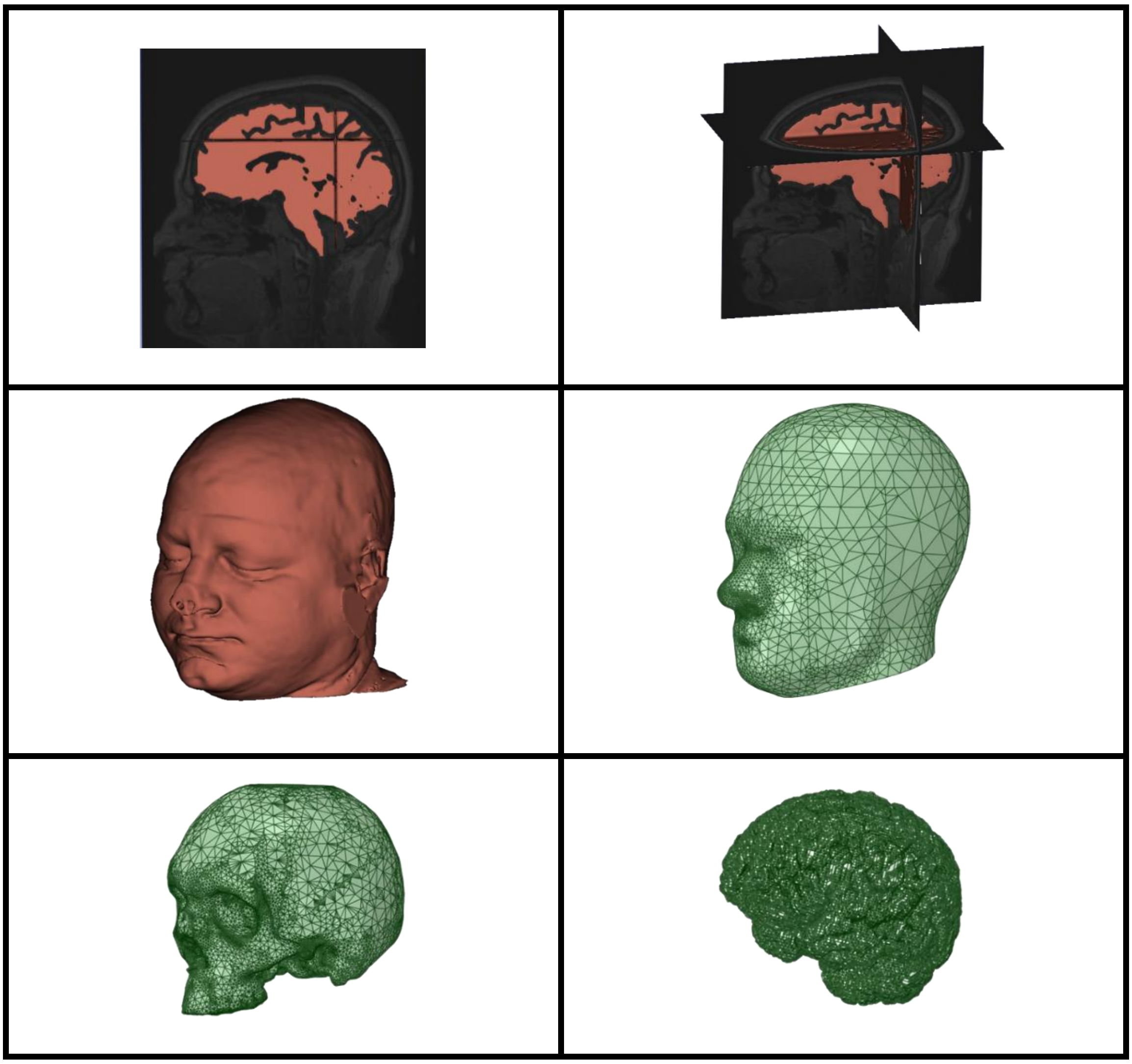


Figure 2: 3D model generated by Image segmentation

3.2 Design of Human Skull Model using CAD

The MRI data generated model of the head geometry of a patient offered considerable accuracy, and it conveyed the elaborate headings of the head model, but the complicated model of the human head during the simulation increased the computational costs. In response to this problem, we came up with a simplified model of the human skull made in CAD. Thus, from the segmented 3D head model the geometry of the skull was derived. This included segmenting the bony structures from the MRI data with the help of segmentation masks. The skull geometry was then stripped down to a simpler form to decrease the number of elements without much affecting the shape and size of the bones. This required lessening of the mesh density and blurring out even more specific anatomical features that would not affect impact simulations also we designed heads in such a manner that our computational cost reduced to as low as possible.

The skull geometry made in CAD will be tried to realistic at the same time we are targeting to study the stresses on skull, so we ignored some of the complex parts of the head like CSF etc. Thus, applying the modeling capabilities of CAD, a realistic but at the same time quite computationally light model of the skull was built. While modeling the Skull bone the majority of skull and face was modeled accurately while keeping in mind the computational complexity of the model.

Other than skull, helmet geometry in assembly form is also made by following the real helmet dimensions like shell thickness and foam thickness so that it can be simulated with head for proper nodal connections foam pad is intersected from the head outer curvature so that proper head shape is imprinted and during FEA forces will be transferred properly. A full shaped helmet is not used because it will increase the computational cost so for simulations, we just used the helmet section which is involved in impact protection.

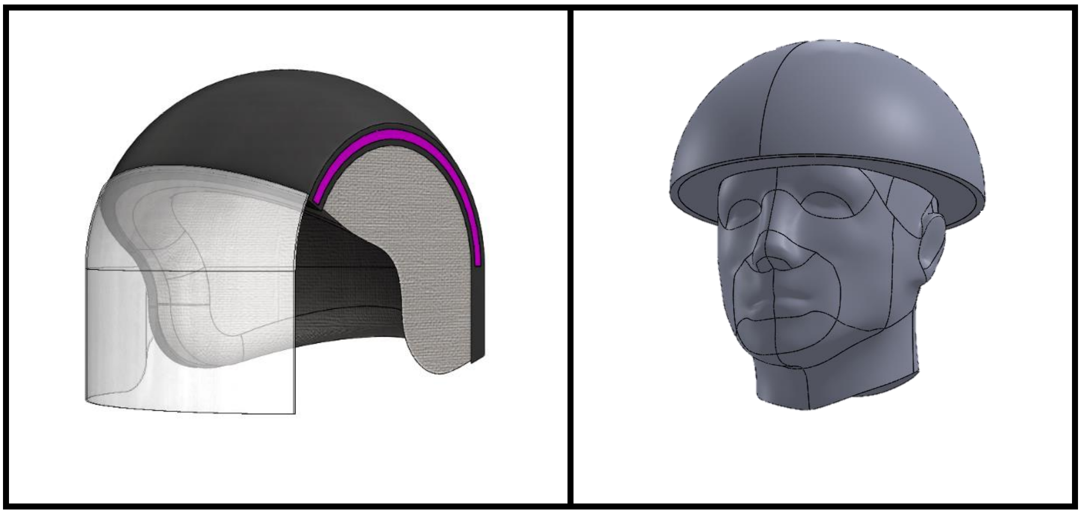


Figure 3: SolidWorks Head and Helmet Model

Some of the targets achieved by making model via CAD:

- Efficiency: Due to the model, costs associated with computations were minimized and great amounts of detail and elaborate simulations could be run in reasonable time.
- Accuracy: Thus, the simplification that took place did not disregard the anatomical features, which made it possible to obtain accurate simulation data.
- Flexibility: CAD software's allowed for the reassessment and alteration of the model for one or another simulation circumstance as required.

3.3 Dynamic Impact Analysis Using FE Simulation

After developing our geometrical model for the simulation, the next step is to select the materials, surface node sharing and applying boundary conditions to replicate the real-world scenarios. The choice of the materials that make up the helmet shell is one of the most sensitive areas of this study. The materials selected must be capable of absorbing the impact, and withstand the loads applied to them; it should also be light and durable. After the material selection the next step is to implement numerical model, meshing, proper boundary conditions, constraints, contacts, controls and interactions, to simulate a real time scenario.

3.3.1 Material Selection

To filter potential materials for helmet shells that have been studied in the literature for their protection efficiency. A review of related literature was undertaken in order to acquire data on several materials used in helmet construction, regarding their mechanical characteristics, impact resistance, and prior uses. Hence, the materials like ABS and Kevlar were focused on because their usage is quite popular, and their previous implementations have contributed to the improvement of helmet functionality. [14][4]. All these materials are mostly available in ANSYS materials library defined by real time testing data available in literature and repos by ANSYS developers.

To establish the criteria for material selection based on the desired properties for helmet shells we have focused on some of these properties. To establish the criteria for material selection based on the desired properties for helmet shells we have focused on some of these properties:

• **Impact Resistance:** The characteristic which makes it possible to absorb and dispel the energy from impact for the protection of the head.

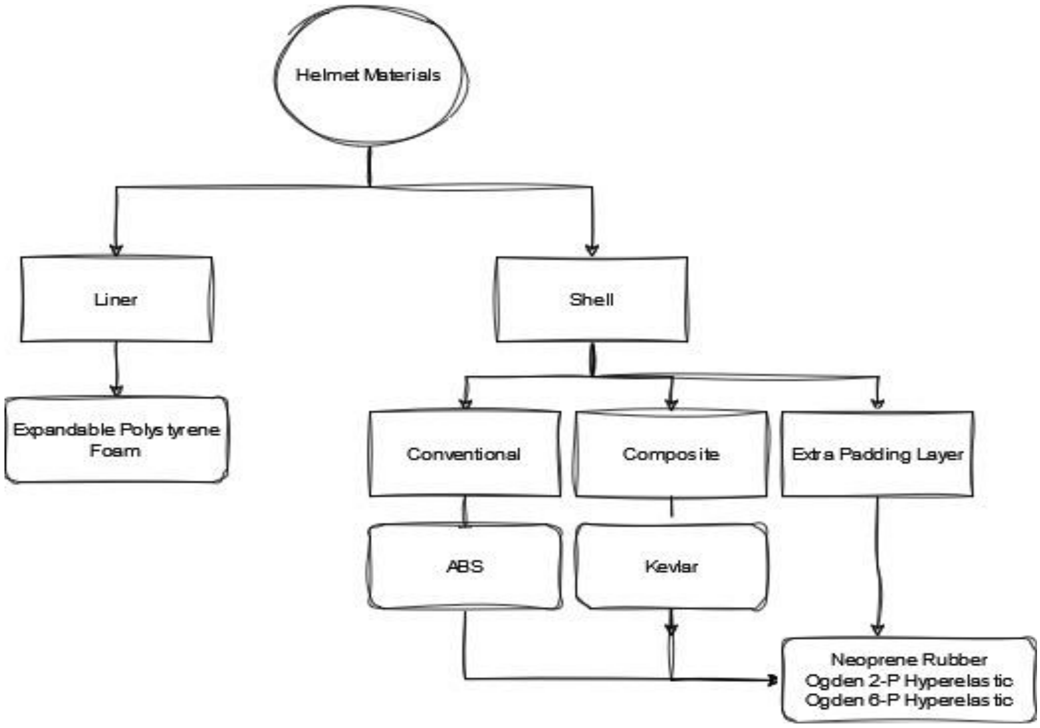
• **Durability:** Difficulties associated with wear-resistance, effects of the surroundings, and abradant degradation.

• **Weight:** Thin to increase user comfort and to minimize fatigue.

• **Cost-Effectiveness:** Demographics and reasonable costs for manufacturing and the ability to scale up.

• **Availability**: Appropriate materials for implementation of what is being taught in the classroom and experiments.

Types of materials used:



When doing our research, we choose these two similar helmets to contrast with our design and material improved helmet. The main inspiration from nature in this case is the spine vertebral disc material and therefore we have selected shell of these material one is very basic polymeric and the other one is composite material as they are widely used all over the world. Among basic polymeric shell ABS is used, as it is a kind of thermoplastic polymer which is highly strong, highly impact resistance and highly durable. It is widely deployed in the construction of helmet shells since it offers a hard plane that can effectively disperse the force of shocks over a wider area thus minimizing the impact densities at any given point. [4]. On other Kevlar is an exceedingly tough and light-weight aramid fiber long recognized for its outstanding strength and mass ratio. It is commonly applied in high impact helmets in sports, military and police uses due to the best protective properties [14].

EPS foam is preferred in the helmet liners because of its ability to offer high levels of energy absorptions. It compresses an impact such that the energy generated by an impact is spread out and the amount of force that would be transferred to the head is minimized. Despite this, EPS is the most effective and light type of foam that gives a good start in the scheme of helmet padding that is used almost in every bike helmet[38].

To add extra protection a padding layer is added in between the hard shell and lining Neoprene rubber possesses strong features dealing with shock absorption as well as flexibility. According to the integration of Neoprene in between the ABS shell stacking, the impact transferring characteristic of the helmet might be improved to absorb impact energy effectively, which in turn lessens the stresses and forces applied to the head.

Hyper elastic Ogden's are used in Ogden based hyper elastic materials to characterize the non-linear stress- strain relationship of elastomers and biological tissues. They are highly flexible materials that can go to large deformations without ripping apart, hence making their ideal candidates for any application that needs to have high energy absorption and dissipation [39].

3.3.2 Numerical model

In our methodology of FEA and Dynamic Analysis these are the key parameters that are used in our system validation and development of Helmet on basis of the simulations.

Key Parameters and Equations:

1. Velocity:

The velocity is one of the most important parameters as it is the main parameter in kinetics and kinematics.

$$v = \sqrt{2gh} \quad \text{(Eq. 1)}$$

Here g is gravitational acceleration and h is dropping height. It is very useful in calculating impact velocity based on drop height.

2. Peak Acceleration:

The peak acceleration is what the accelerometer in the head forms. This is one vital parameter in injury criteria assessment. But in our study, we have used this to validate our model as our main concern is stress analysis.

$$a = \frac{\Delta v}{t} \quad \text{(Eq. 2)}$$

3. Von Mises Stress:

The Von Mises stress (σvm) is calculated by using the formula:

$$\sigma vm = \sqrt{\frac{(\sigma 1 - \sigma 2)^2 + (\sigma 2 - \sigma 3)^2 + (\sigma 3 - \sigma 1)^2}{2}} \quad \text{(Eq. 3)}$$

where σ1, σ2, and σ3 are the principal stresses. Representing different stress orientations.

4. Kinetic Energy (KE):

The kinetic energy just before collision is given by:

$$KE = \frac{1}{2} m v^2 \quad \text{(Eq. 4)}$$

where m is the mass of the head form and helmet, and v is the velocity at impact.

5. Momentum (p):

Momentum is calculated using:

$$p = mv \quad \text{(Eq. 5)}$$

where m is the mass, and v is the velocity. Which further converted to impulse when the head form hits the impactor.

6. Impulse:
Impulse is the rate of change in momentum with respect to time represented as:

$$\Delta F = m\frac{\Delta v}{\Delta t} \quad \text{(Eq. 6)}$$

3.3.3 Meshing

The meshing used in our simulation is of hybrid type having tetrahedral as well as octahedral mesh. This type of meshes are used where geometry is not of the simple type but instead of it have sharp curves or curvatures unlike a simple sphere or cube so in this type of geometry this type of meshes are used. Second meshing is done to divide our body into finite small elements and effect of forces are visible on these finites meshes each as a result.

3.3.4 Boundary Conditions

Boundary conditions are applied to give the physics simulator instruction that which body is in moving state, and which one is one is in static position. In our case we have fixed the impactor as a rigid wall and made our head form model move with some velocity in the direction of the impacting wall to collide with the impactor.

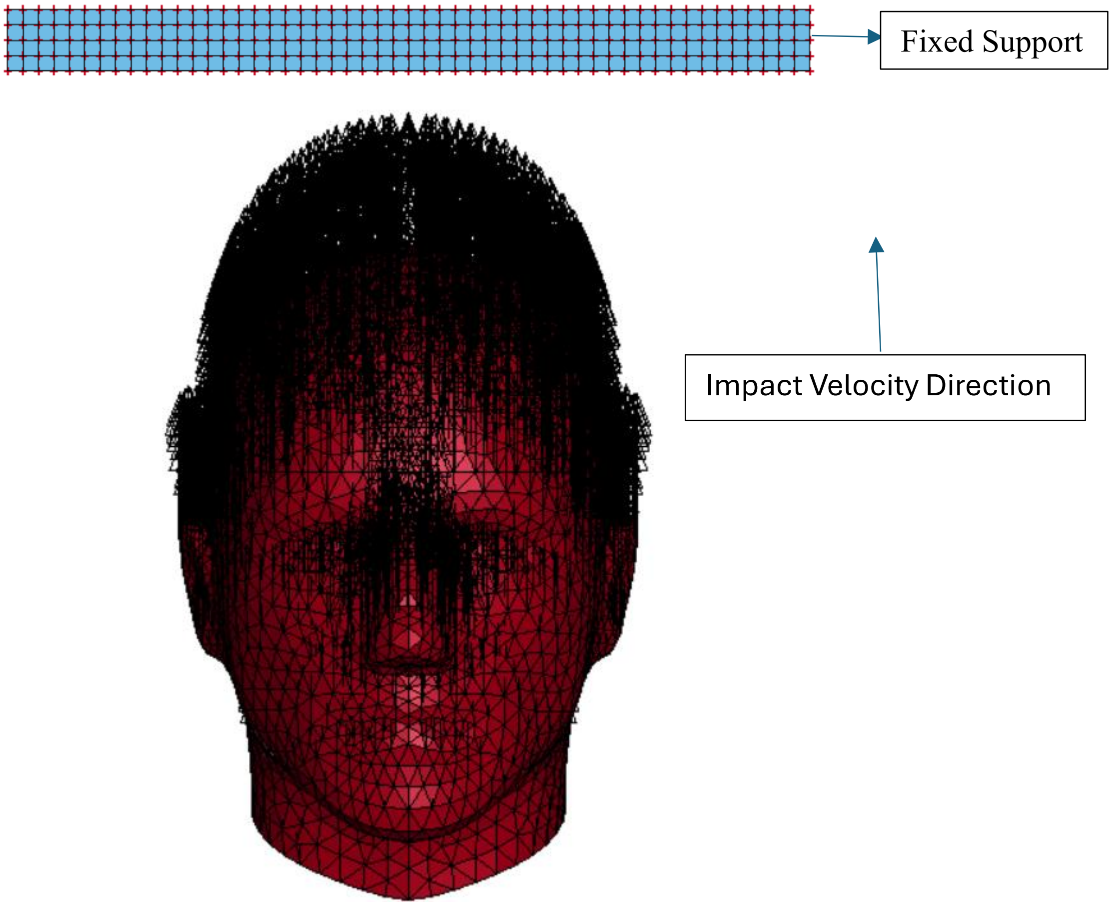


Figure 4: Boundary Conditions

3.3.5 Contacts

Contact is very useful for force and stresses transferring as in model in assembly form didn't transfer stresses unless and until we have tied bodies contacting with each other surface to surface such that the two different bodies will share common nodes among them. Then the forces will transfer from helmet shell to foam and then foam to head. In this manner we will simulate impact.

3.3.6 Controls

Sometime some controls are also used to avoid errors like in our study we have used hourglass control to transfer stresses properly even the meshes are deformed or distorted with zero strain this control allows the proper transferring of stresses without failure of stress propagation. Other than this time steps controls are used to apply time steps such that proper forces are transferred during the impact

3.3.7 Interactions

At time of impact, it is also very important to define the interaction conditions like either the interaction between the two bodies is either idea means frictionless, or it have some frictional effect between the surfaces of the two interacting bodies.

3.4 Simulations

After successfully applying materials and boundary conditions then we first validated our model using a drop test and checked the validity of our study to see that we are getting results from our simulations which are good enough to generate real time results.

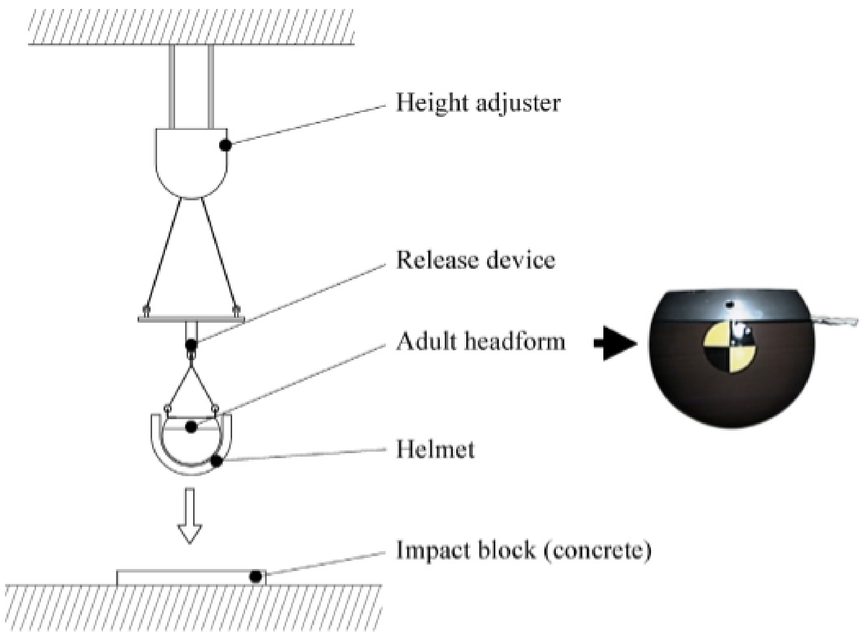


Figure 5: Drop Testing Setup

After that, we will do study of head impact with different impact scenarios like different drop heights or impact velocities both are interconnected with each other as more height tend to more impact velocities. Also done these impact scenarios on different helmet materials so that we can evaluate the most efficient helmet based on their results comparison. In our Simulations as discussed before we have used one very basic helmet with ABS shell and EPS foam, Second one with KEVLAR (Aramid/Epoxy) shell with as they are more advanced to the ABS shell helmet, Third one is our very own design having three layered shell helmet having two shell of convention materials like ABS or Kevlar but one layer is of some basic rubber like neoprene or advanced materials like hyper elastic material. Based on these materials and all other parameters like boundary conditions applied we will get the results which will then be analyzed for conclusion.

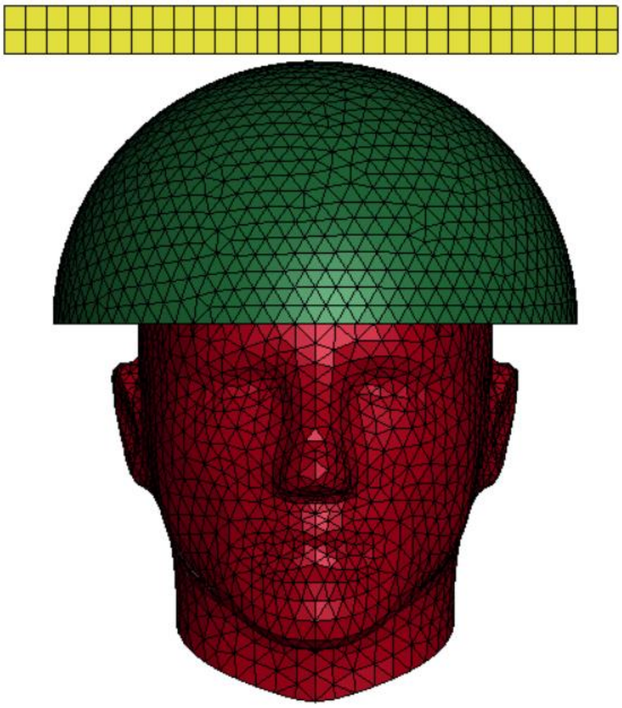


Figure 6: Simulation Model

3.4.1 Post Processing

After executing the simulations comes the final part of result visualization and data processing. As we have used ANSYS(LS-DYNA) we got the result visualization as stresses contours with data of stress with respect to time which is post processes in graph plotting and analysis tools like Origin or MATLAB to compare results with each other.

These are all very basic but very useful parameters that help our research to conduct impact testing with good and smooth results. Based on the results, we analyzed the performance of different materials at different impact conditions so that we can conclude the performances of all those helmets.

Chapter No. 4

4 Results and Discussion

4.1 Feasibility Study

Feasibility study is very important to simulate any scenarios in physics simulators without the validation of results we cannot justify the authenticity of the study. So, first validation results will be discussed here in this chapter as we have authenticated our study based on our validation of our simulation. We have followed an experimental testing result from literature based on drop test to calculate the peak acceleration in the ARUP head form based on these experimental setups we have simulated our drop test and surprisingly we got results very similar to the actual testing result which are without helmet peak acceleration at accelerometer is 2818m/s^2 and in our simulation, we got 2644m/s^2 at the same time it has 6.17% error only. In case of drop test with helmet on ARUP head form peak acceleration is 1068m/s^2 in experimental testing and in our simulation, we got 1048m/s^2 peak acceleration as it can be seen in figure (7) and figure (8) which is only 1.87% error from the real time data[40]

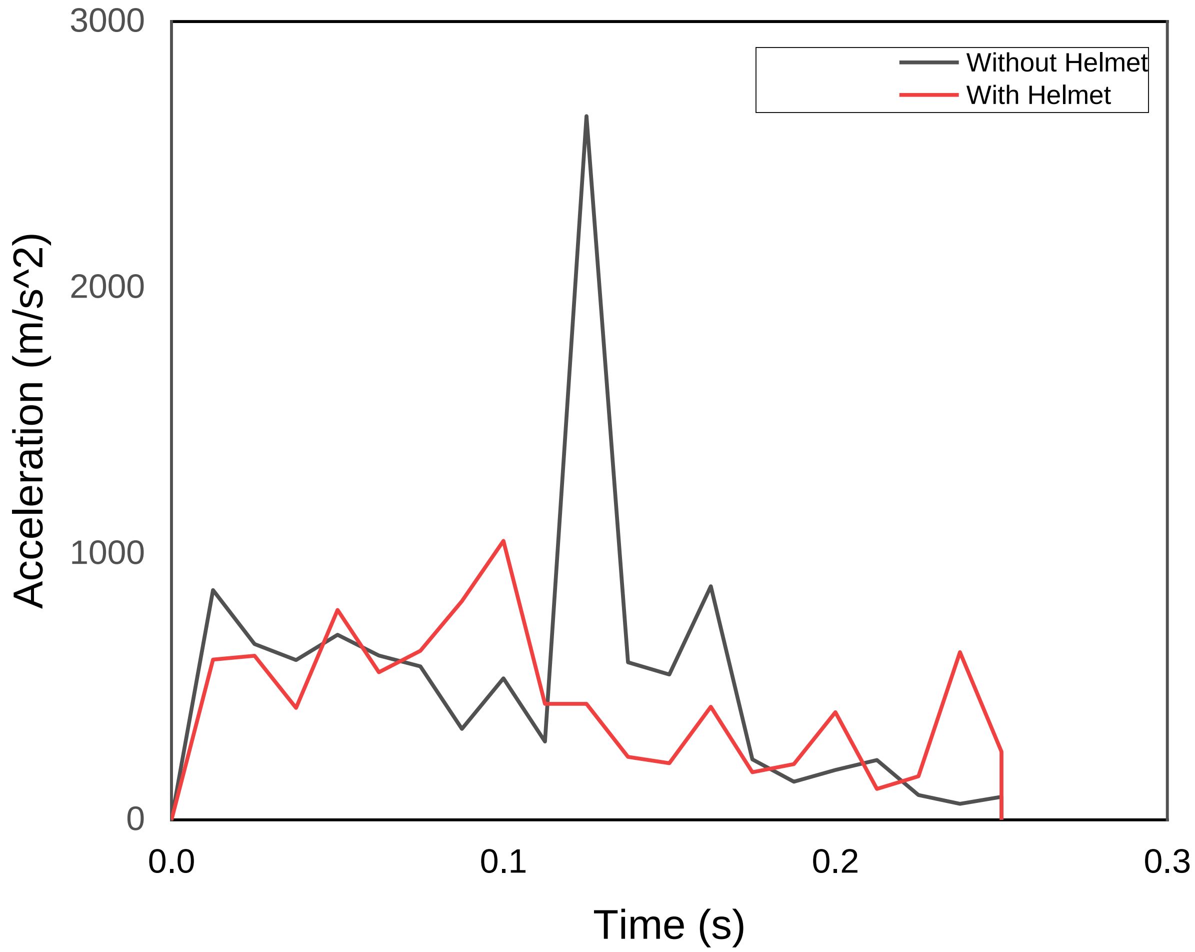


Figure 7: Peak Accelerations

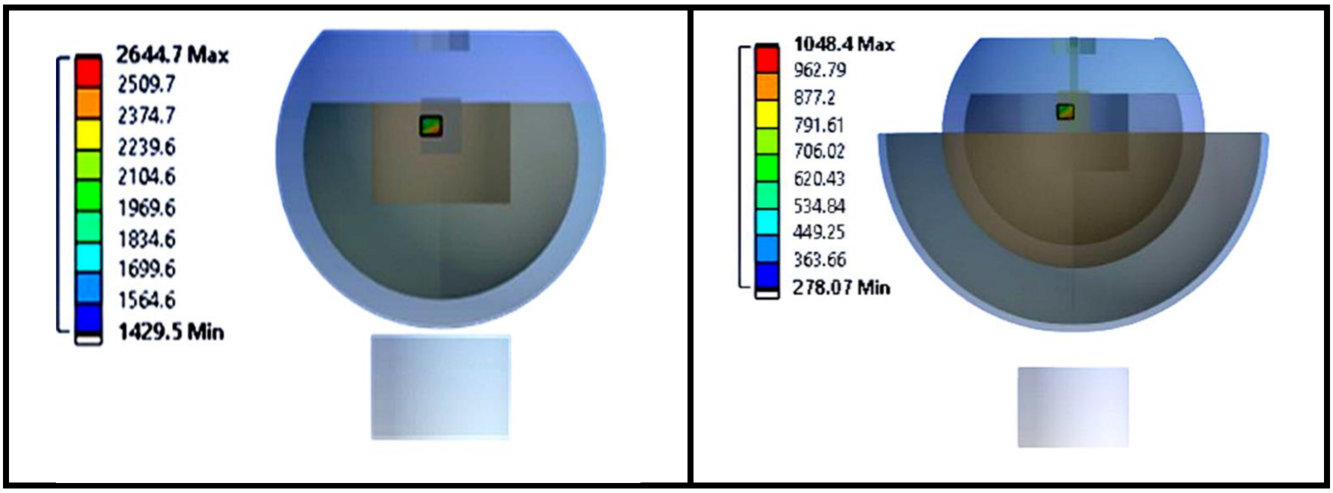


Figure 8: Peak Acceleration with Helmet

Other than that, the momentum of the head form can be seen from the figure (9) graph which is validated by numerical model equation without helmet p=mv= 4.3Kg*3.13m/s=13N-s in the graph first it is in negative and after impacting it is in positive which is simply indicating change of direction of momentum. With helmet mass added which is almost 0.5Kg p=mv=4.8Kg*3.13m/s=15N-s. Getting hand calculated figures from these physics equation same as simulation are very useful and indicating us about the actual following of real time physics by the simulator while doing computational studies for the impact testing.

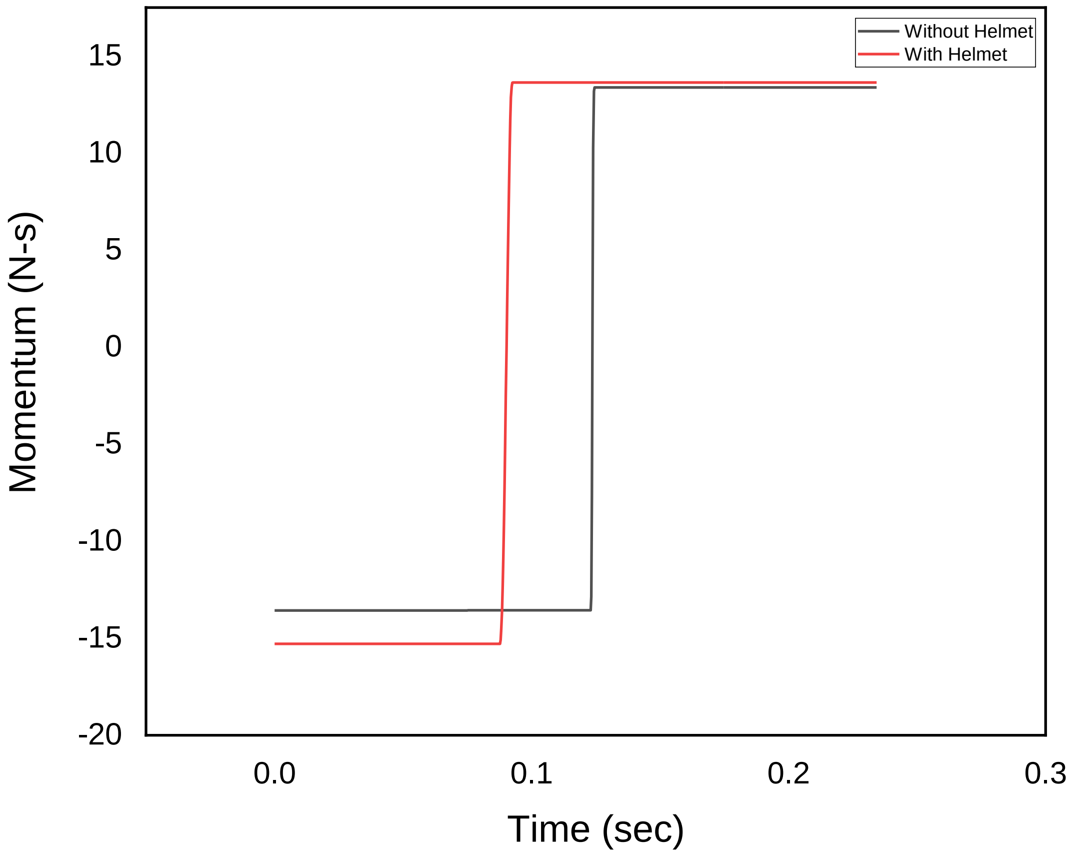


Figure 9: Momentum Graph

In the next figure (4.4), which is Kinetic Energy graph without helmet there is 21J of kinetic energy which comes after K. E=1/2*m*v^2=0.5*4.3Kg*(3.13m/s) ^2=21J of energy which after impact lost a few joules of energy. But with helmet there is 23.5J of energy which comes out by K. E=1/2*m*v=0.5*4.8Kg*(3.13m/s) ^2=23.5J which after impact drops to almost 19J it is the energy lost during the head form impact. Again, the hand calculated values are almost identical to the simulation calculations. That can be seen in figure (10) which shows KE of head form with and without helmet.

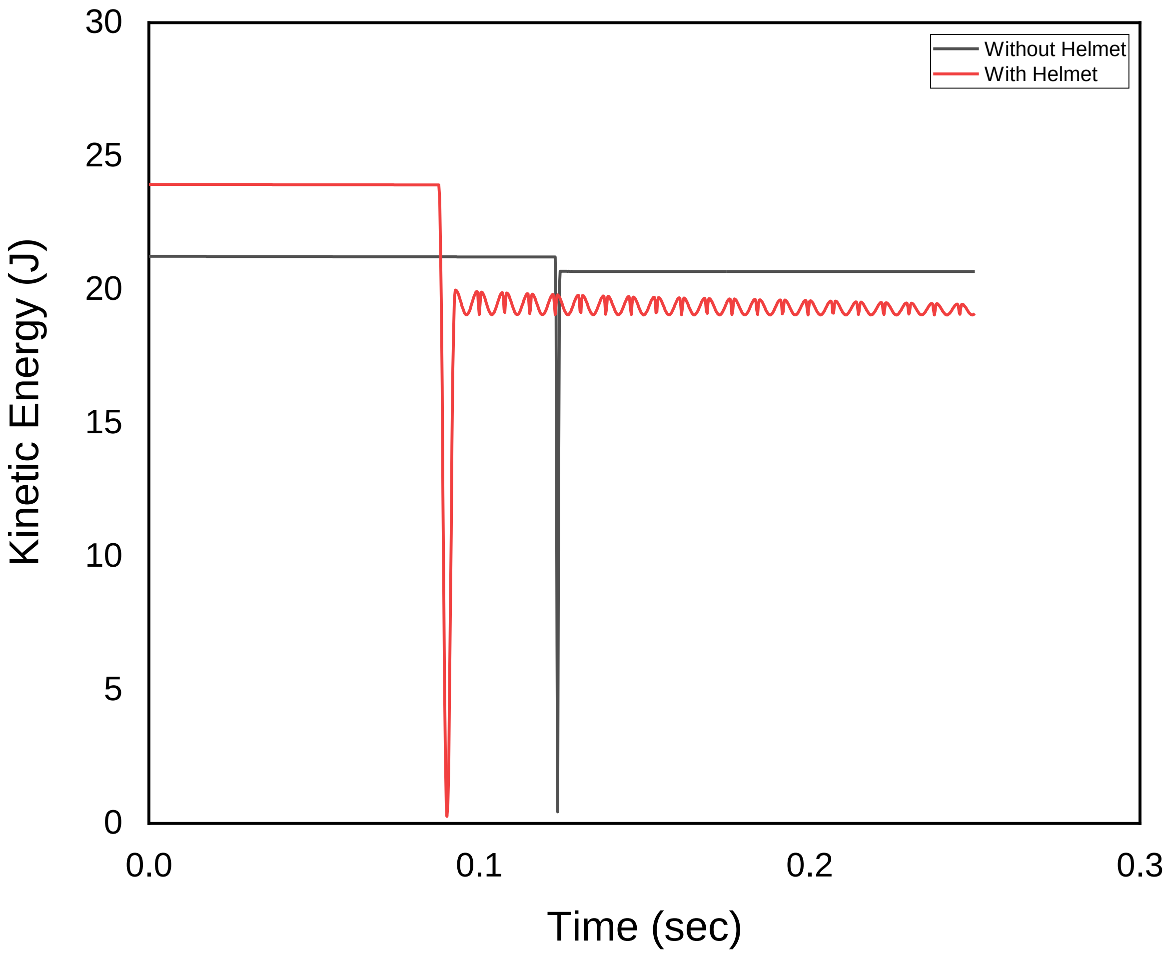


Figure 10: Kinetic Energy Graph

Also stress analysis is also very important to authenticate our research work mostly head mass ranges from 3.5kg to 5kg ranging from kids to adults in our case our Arup head form is almost 4.3kg in mass which cause it stress when impacted with velocity as it can be seen in figure (11) the stress value here is 19.23MPa which is also cross validated from literature and at 3m/s velocity stress level on head range from 15MPa to 35Mpa depends on impact angle and head mass[41]. The variations in the stress values are due in ARUP head form model and humanoid head form model is due to the different masses secondly the shape of the head forms an ARUP is totally round on the other humanoid head form is a little bit oval shaped which cause stress concentration at impact region more and more.

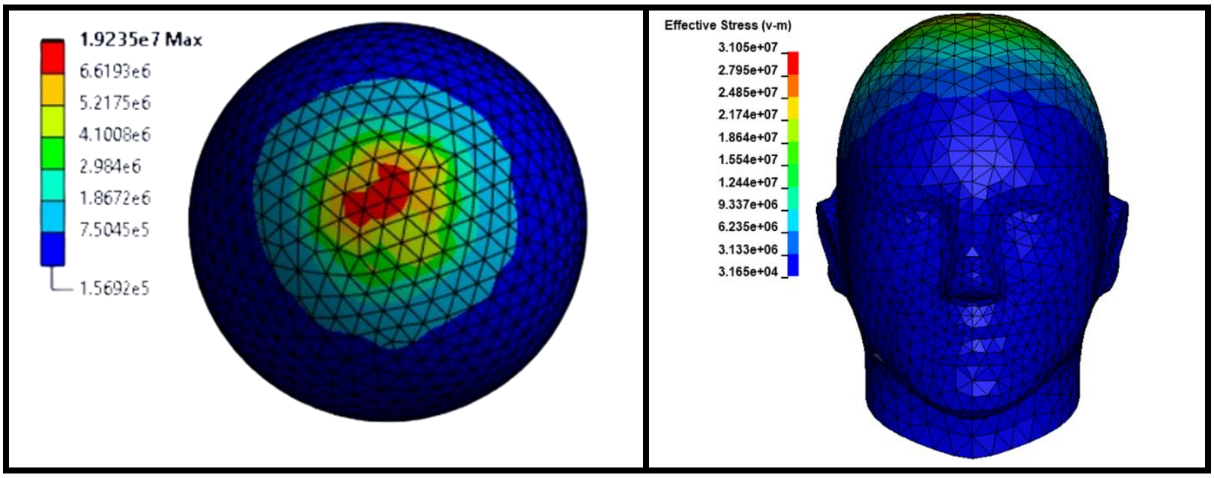


Figure 11: Von Misses Stress

The results of head form are a little bit higher which is 31MPa is due to its mass which is 4.8Kg higher than the Arup head form mass which is 4.3 Kg but cross validating it from literature it has the acceptable results as it is in range of the results, we have seen in literature[41].

4.2 Proposed Study

After validation we done simulation with different impact velocities so that we can observe the stress values on skull.

After validation we have done simulation with different impact velocities so that we can observe the physics of impact velocities as by increasing velocities stress values in MPa also increasing which is due to increasing impacting momentum. Which can be seen in the given table (1) and figure (12).

Table 1: Impact velocities corr. to peak Stress

Impact Velocity(m/s)	1	1.5	2	2.5	3	3.5	4	5	12
Peak Stress (MPa)	26.10116	27.00138	28.53524	30.04363	31.04903	32.73196	33.52976	36.72652	47.58499

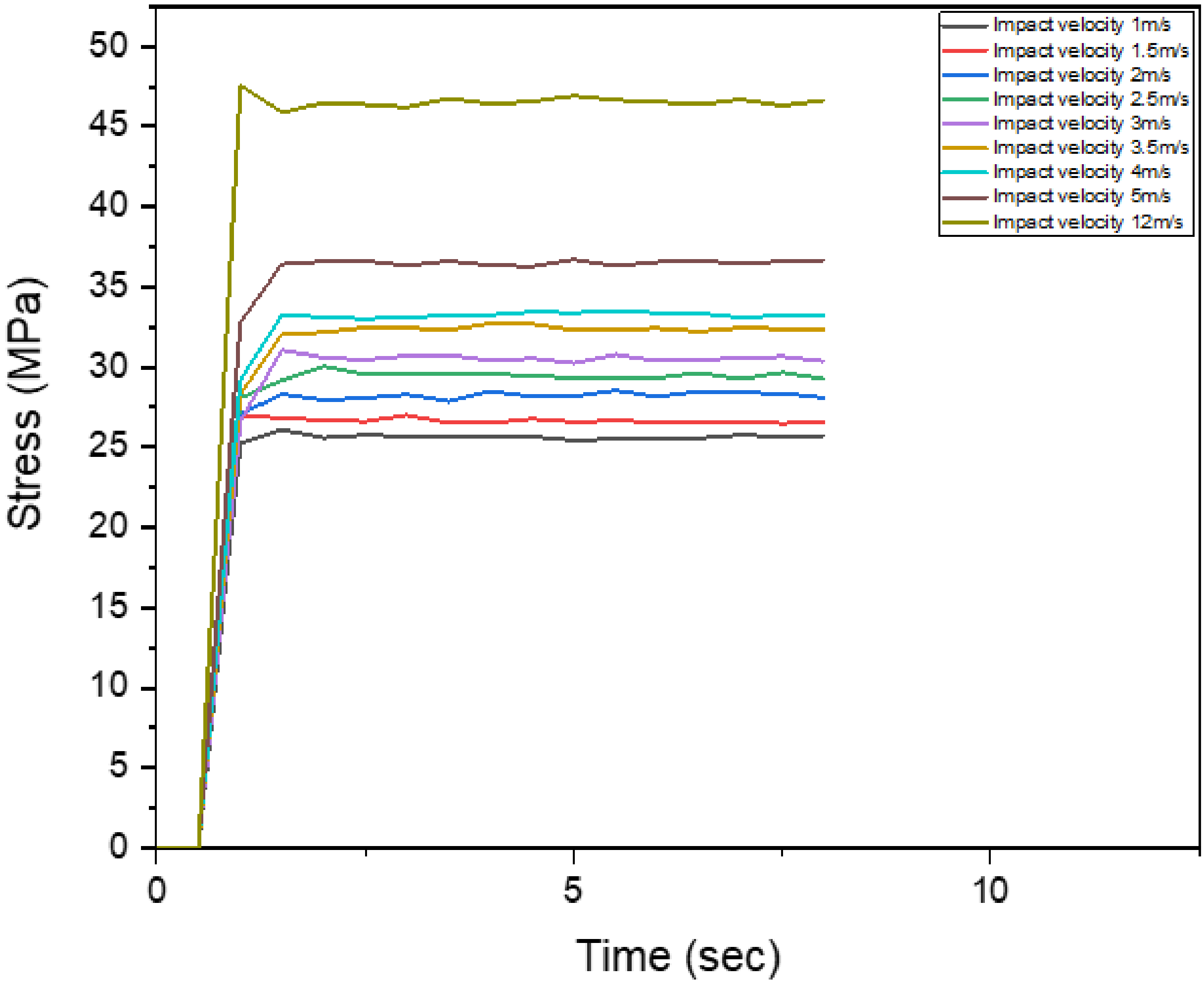


Figure 12: Stress values at different Impact Velocities

After validation we done simulation with different impact velocities so that we can observe the performance of each shell helmet so that we can found better performing materials for helmet material and design optimization. First, we have done some impact simulations for ABS, Kevlar, Neoprene Rubber Padded, ABS with Hyper elastic Ogden 2 parameters stacked layer, ABS with Hyper elastic 6 parameters stacked layer, and finally Kevlar with Hyper elastic 6 parameters stacked layer. All these simulations are done based on our literature review and based on the simulation results we have found better solutions for Helmet.

First, we have simulated ABS shell helmet with 4 different impact velocities ranging from low impact velocity to average bike velocity with peak stresses on skull can be seen from table (2) and figure (13) respectively.

Table 2: ABS Peak Stress and perc. reduction

Impact Velocity (m/s)	3	4	5	12
Peak Stress (MPa)	5.0	7.30	9.87	25
Percentage Stress Reduction (%)	83.89644	78.2283	73.12569	47.46242

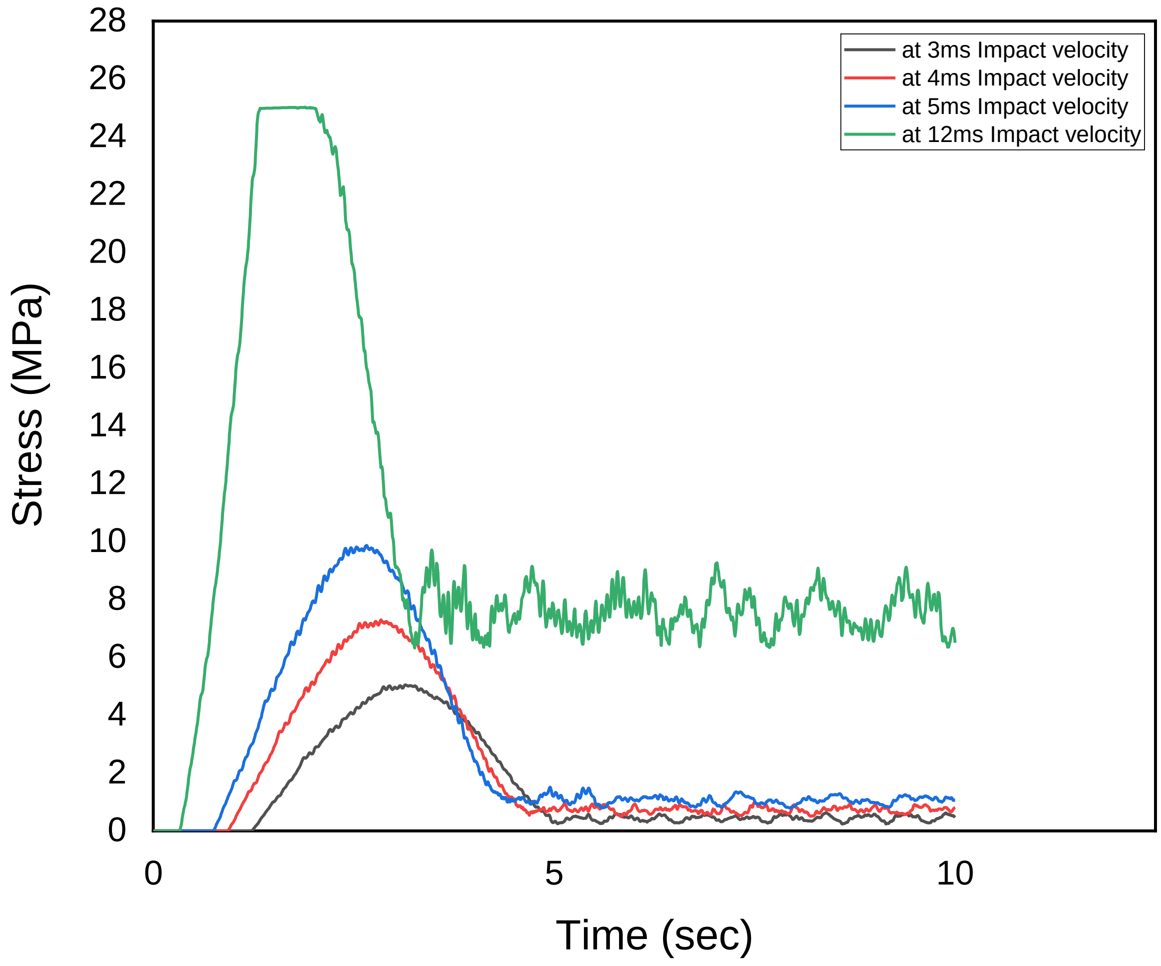


Figure 13: ABS Stress plot at diff. Velocities

Then we simulated a more advanced composite helmet having Aramid Epoxy (Kevlar) shell which have as such same results of stresses on skull at low impact velocities. But at higher velocity it outperformed the ABS shell Helmet which can be seen table (3) and figure (14).

Table 3: Kevlar Peak Stress and perc. reduction

Impact Velocity (m/s)	3	4	5	12
Peak Stress (MPa)	5.271707	7.055917	8.795009	21.92226
Percentage Stress Reduction (%)	83	78.97	76.0527	53.9303

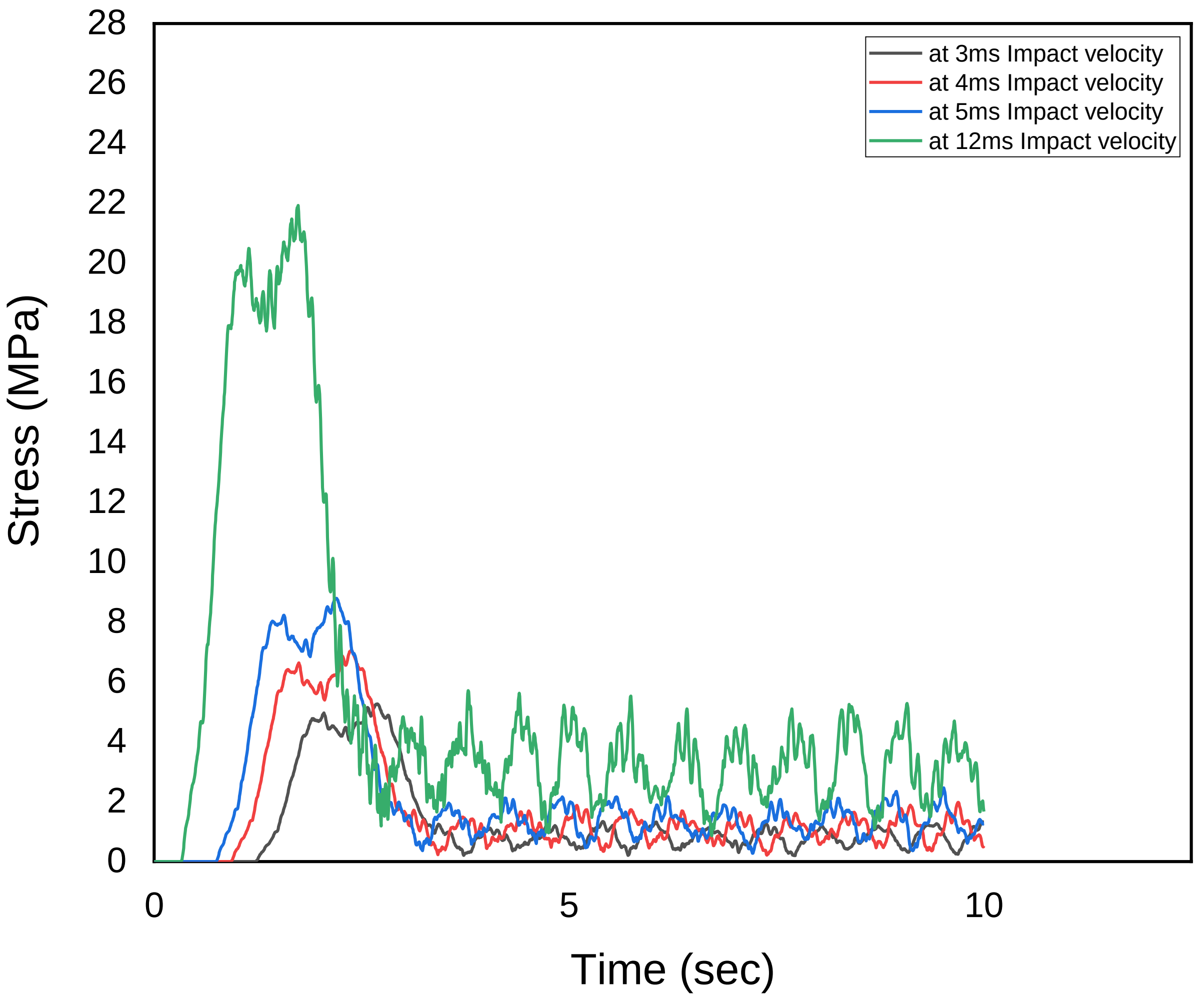


Figure 14: Kevlar Peak Stress at diff. velocities

After simulating these basic results, we have further optimized the shell design by replicating stacking pattern of spine with hard shell layer than below it rubbers shell than again below its hard-shell layer. And for a very basic simulation we use ABS as hard shell and Neoprene Rubber as layer sandwiched between ABS Shells whose results can be seen in the given table (4) and figure (15).

Table 4: Neoprene Rubber Peak Stress and perc. reduction

Impact Velocity (m/s)	3	4	5	12
Peak Stress (MPa)	5.366162	7.939776	10.61207	25.03492
Percentage Stress Reduction (%)	82.71713	76.32021	71.10516	47.38904

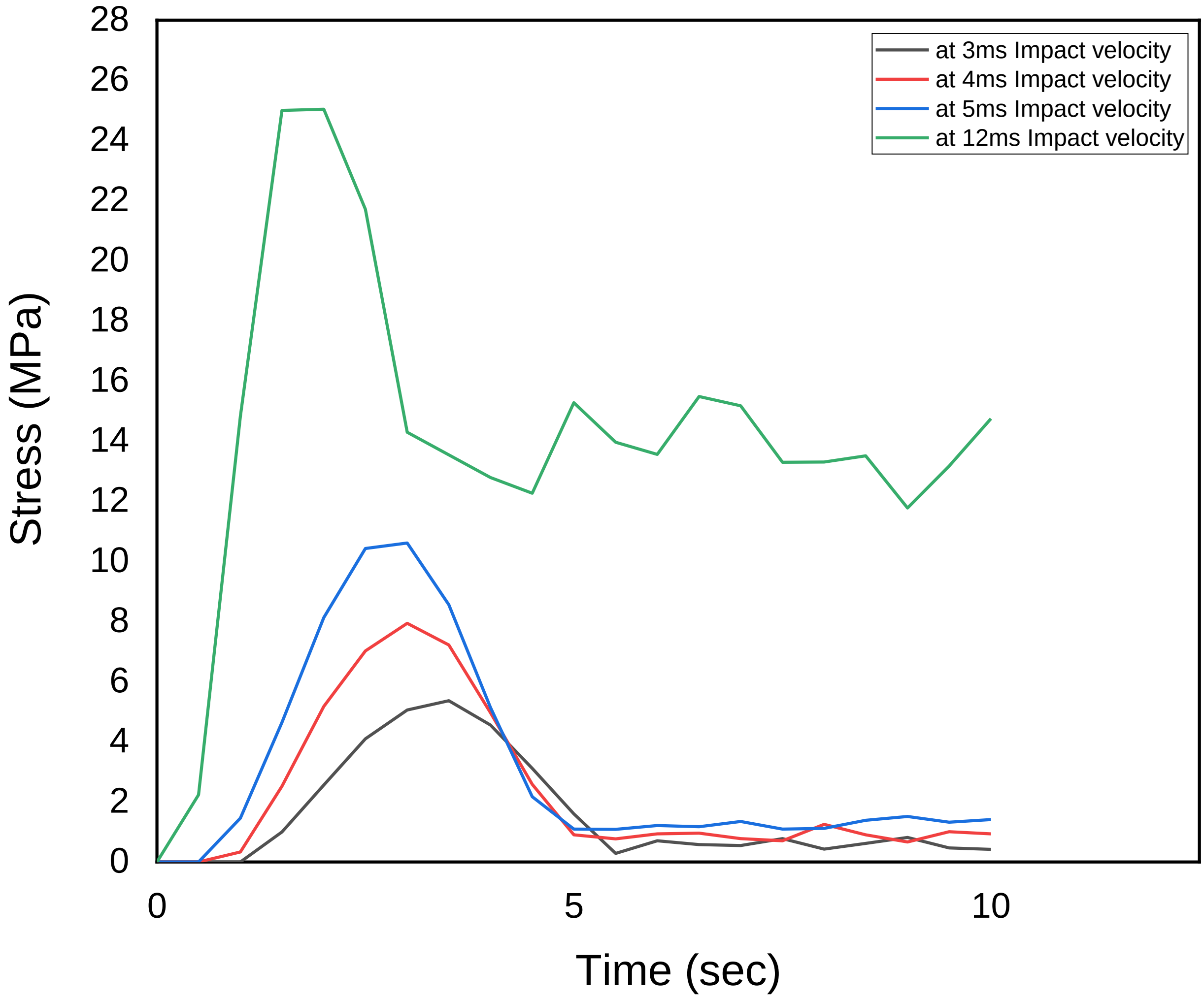


Figure 15: Neoprene Rubber Peak Stresses at diff. Velocities

This Ogden 2 parameters hyperelastic stacked with ABS shell type has good results at low impact velocities compared to the previous one, but it is still not good enough at higher velocities. Which is due to high plastic deformation in helmet shell hyper elastic material doesn't getting enough time to restore its shape which is in fact its property to retain its shape which is prohibited by low restoration time and plastic deformation in ABS shell results can be seen in the above table (5) and figure (16).

Table 5: Ogden 2 Parameter Hyperelastic Peak Stress and perc. reduction

Impact Velocity (m/s)	3	4	5	12
Peak Stress (MPa)	3.288293	5.550044	8.323572	25.01425
Percentage Stress Reduction (%)	89.40935	83.44741	77.33634	47.43247

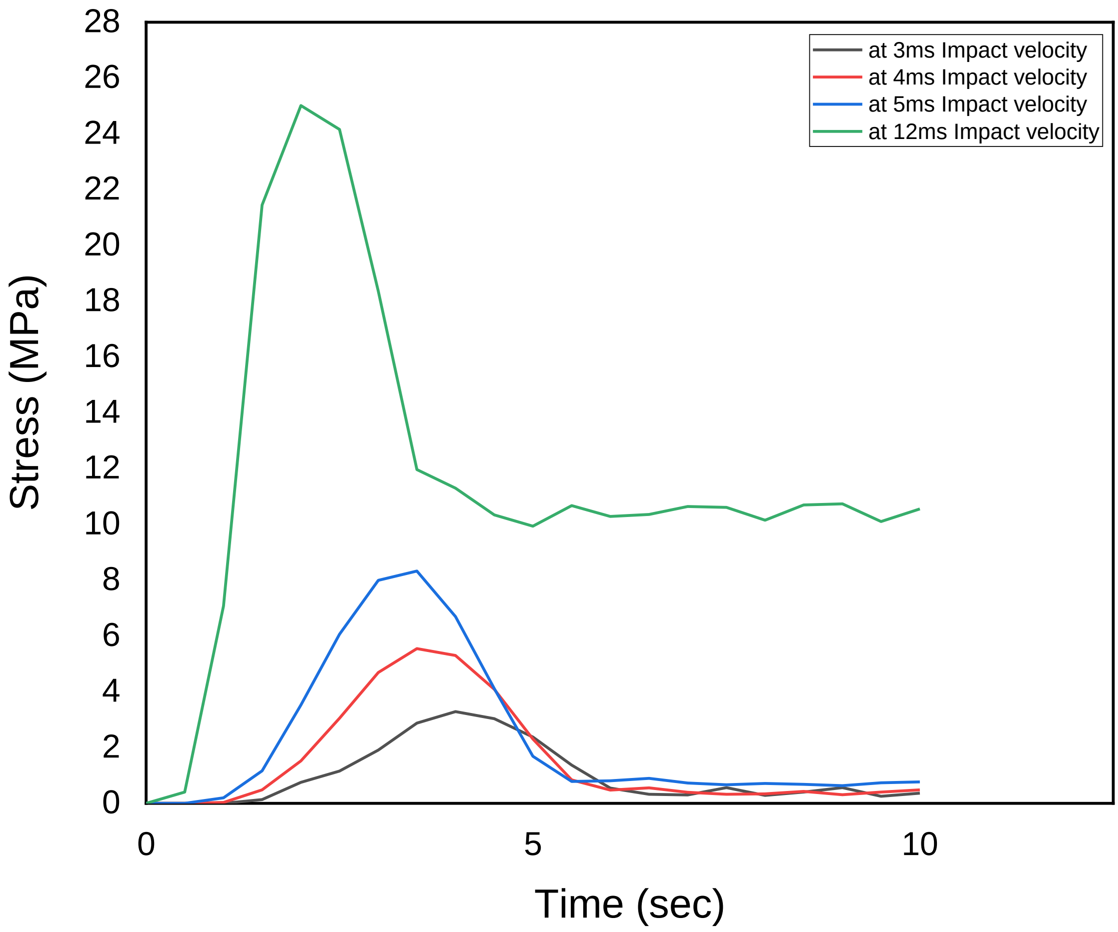


Figure 16: Ogden 2 parameter hyperelastic Stresses at diff. Velocities

To see further improvement in hyper elastic model we used 6 parameter Ogden model it shows some improvement at low velocity impacts as compared to all previous one materials and designs but at higher impact it is still not good due to the same reasons as discussed in above section. Results can be seen in the above table (6) and figure (17).

Table 6: Ogden 6 Parameter Hyperelastic Peak Stress and perc. reduction

Impact Velocity (m/s)	3	4	5	12
Peak Stress (MPa)	3.060643	5.37486	8.445875	25.01562
Percentage Stress Reduction (%)	90.14255	83.96988	77.00333	47.42961

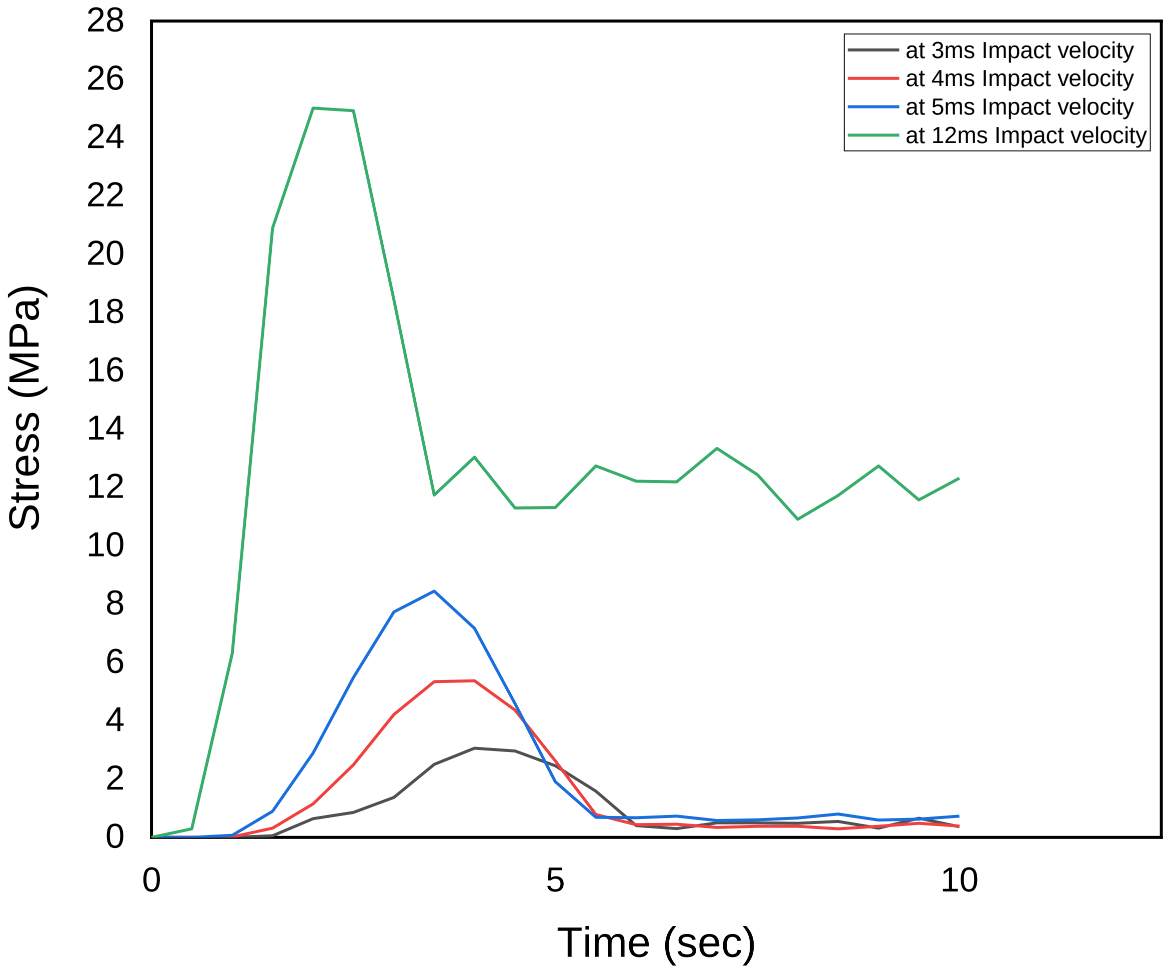


Figure 17: Ogden 6 parameter hyperelastic Stresses at diff. Velocities

By inspecting all the results from the previous simulations, we have seen Kevlar in conventional style helmet with good results and secondly Ogden hyper elastic 6 parameter stacked helmet shell so to investigate further improvement we have used Kevlar as hard shell instead of the ABS and we got very fine results in the stress reduction which can be seen in the above table(7) and figure(18).

Table 7: Kevlar and Hyperelastic Peak Stress and perc. reduction

Impact Velocity (m/s)	3	4	5	12
Peak Stress (MPa)	3.261204	5.028497	5.766589	17.86331
Percentage Stress Reduction (%)	89.4966	85.00288	84.29857	62.46021

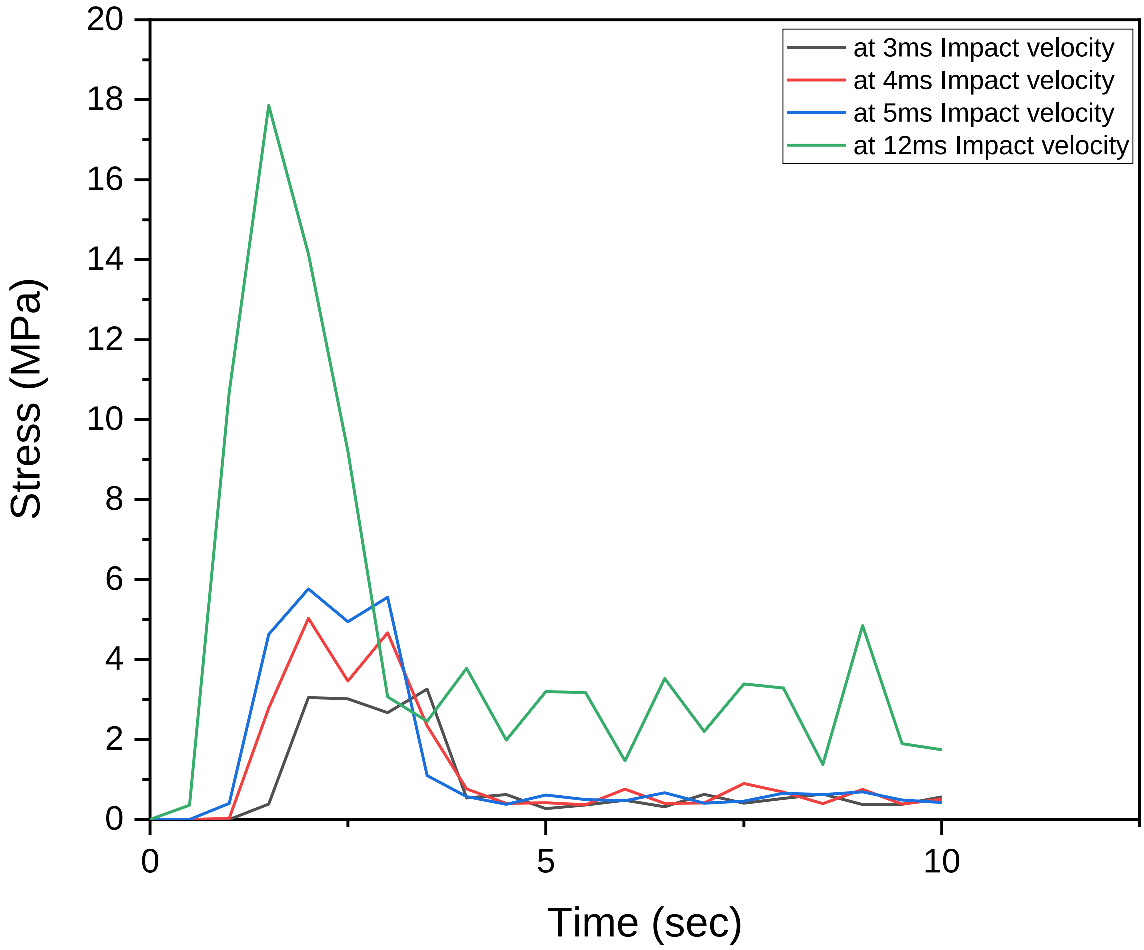


Figure 18: Kevlar and hyperelastic Stresses at diff. Velocities

For further understanding these are some graphs for comparison of result at different speed and different materials. At 3m/s, 4m/s, 5m/s, and 12m/s respectively shown table (8) and in figure (19), figure (20), figure (21) and figure (22).

Table 8: Overall Comparison of all materials

Sr No.		Velocity 3m/s	Velocity 4m/s	Velocity 5m/s	Velocity 12m/s
1	**Skull (MPa)**	31.04903	33.52976	36.72652	47.58499
2	**ABS (MPa)**	5	7.3	9.87	25
3	**Kevlar (MPa)**	5.271707	7.0559165	8.795009	21.92226
4	**Rubber Padded (MPa)**	5.366162	7.939776	10.612068	25.03492
5	**Ogden 2parameters (MPa)**	3.28829275	5.550044	8.323572	25.014254
6	**Ogden 6Parameters (MPa)**	3.06064275	5.3748595	8.445875	25.015616
7	**Composite 6 parameters (MPa)**	3.26120375	5.028497	5.7665885	17.863306

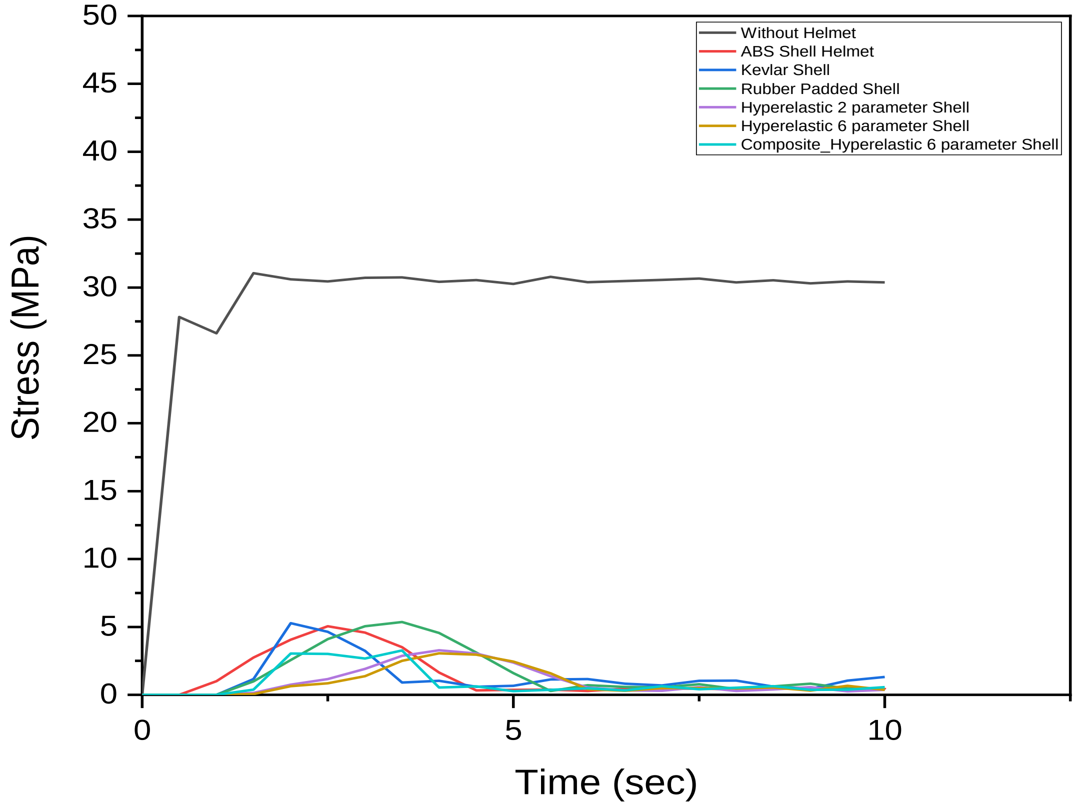


Figure 19: Stress levels at 3m/s

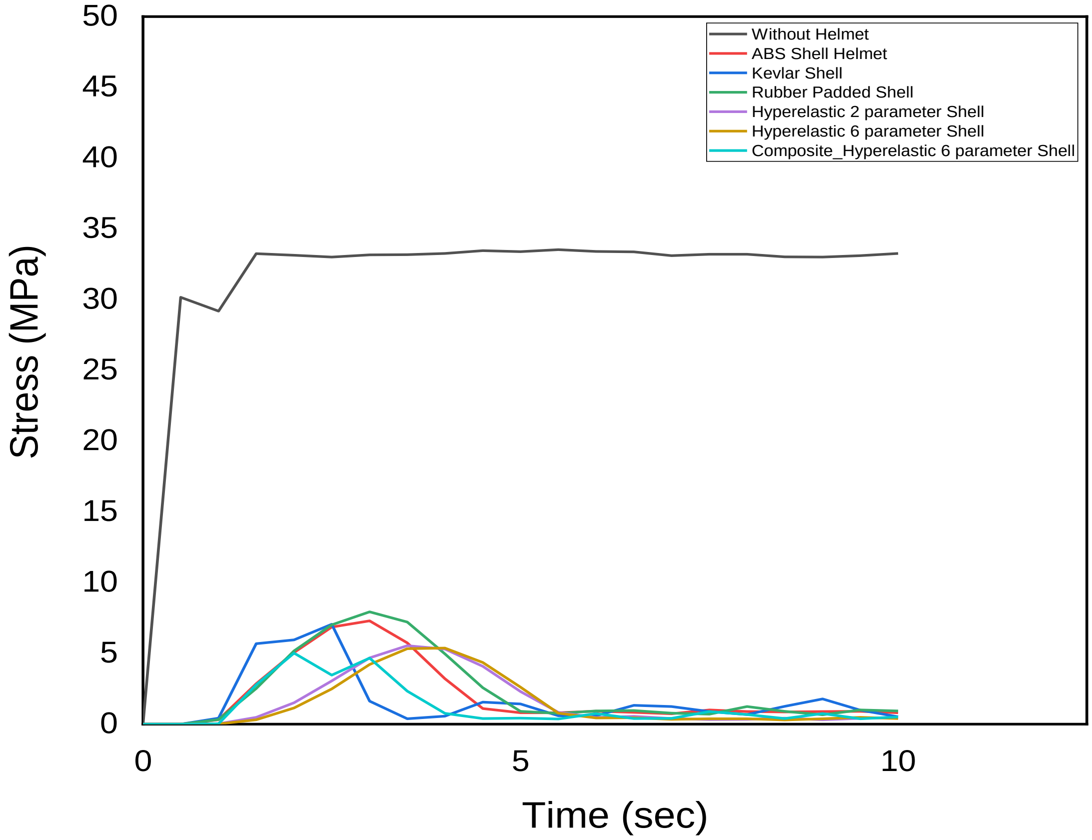


Figure 20: Stress levels at 4m/s

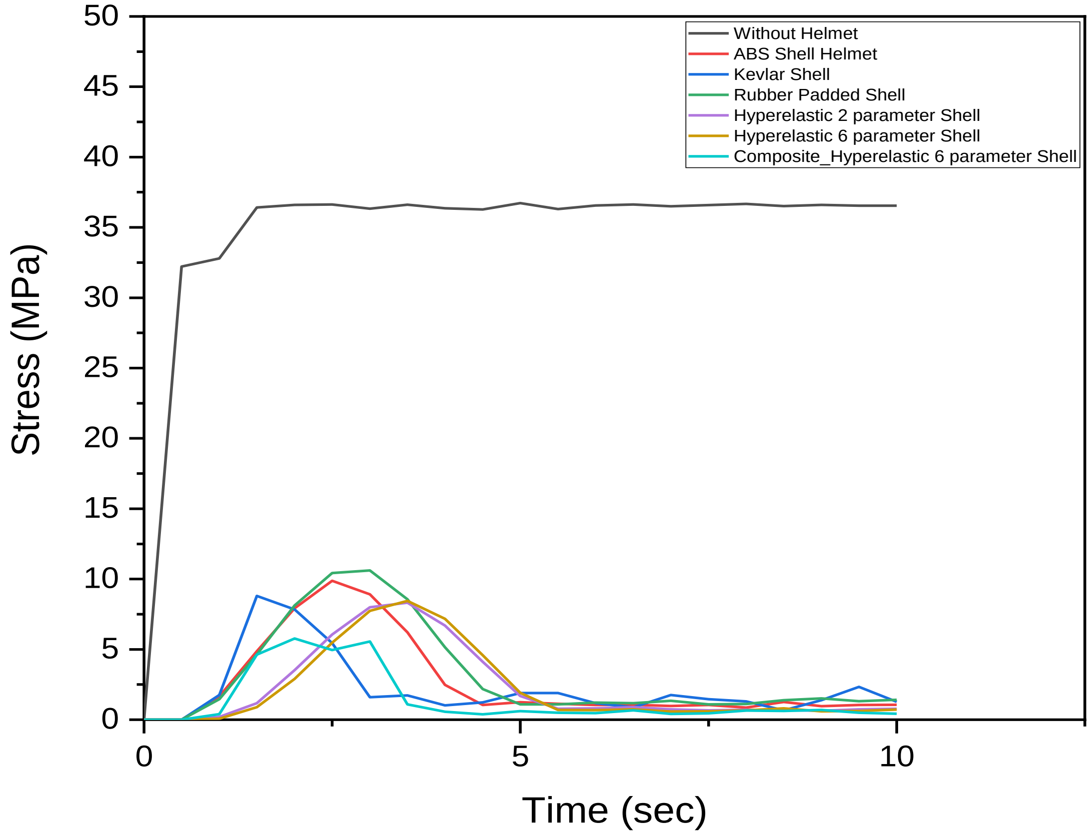


Figure 21: Stress levels at 5m/s

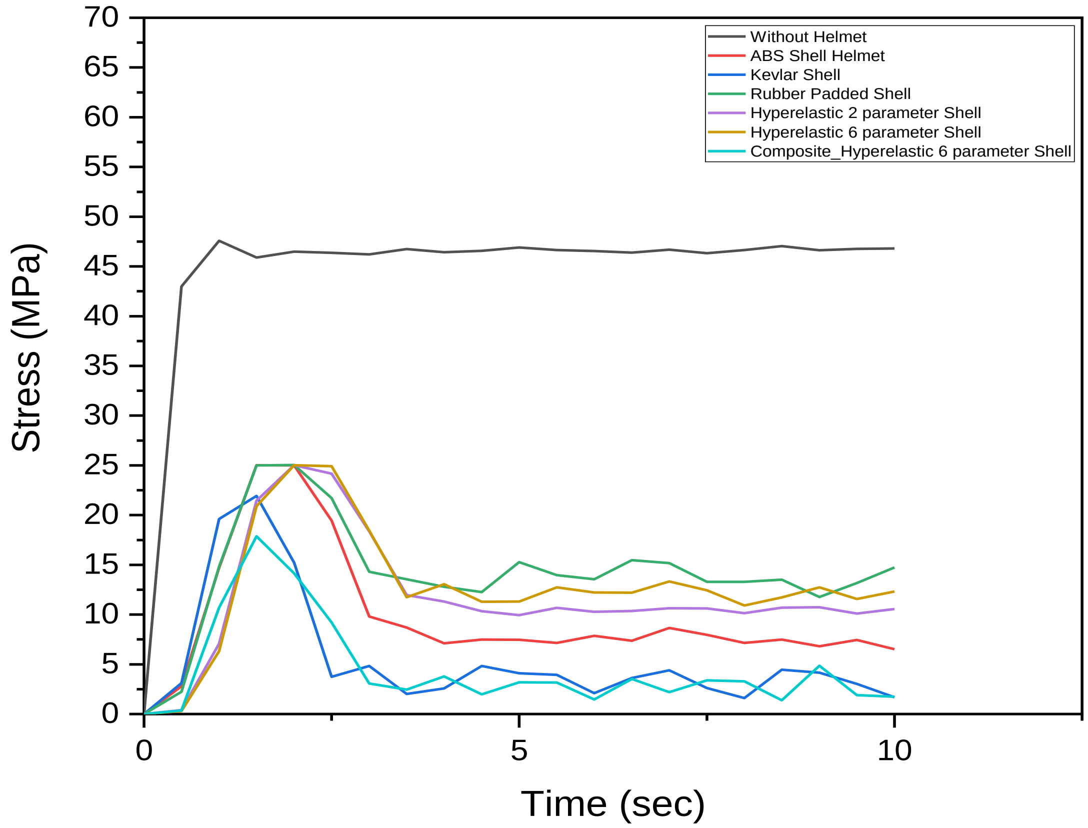


Figure 22: Stress levels at 12m/s

Chapter No. 5

5 Conclusion and Future Work

5.1 Conclusion

The study details the methodology for selecting, designing and evaluating materials for helmet shells and padding, focusing on ABS, Kevlar, EPS foam, Neoprene rubber, and Ogden-based hyperelastic materials. These were chosen based on impact resistance, energy absorption, and durability through literature review, material property analysis, and practical considerations.

Stress values (in MPa) were recorded at 3ms, 4ms, 5ms, and 12ms for materials used in helmet design, including ABS, Kevlar, rubber-padded, Ogden 2-parameter, Ogden 6-parameter, and composite hyperelastic materials, compared against the skull baseline. ABS and Kevlar significantly reduced stress, especially at longer impact durations. Rubber padded materials showed consistent performance, Ogden 2-parameter materials excelled in early milliseconds, and Ogden 6-parameter materials performed similarly with slight variations. Composite hyperelastic materials were most effective at 12ms.

Stress reduction percentages demonstrated the effectiveness of each material. Kevlar and ABS showed significant reductions, with Kevlar performing better over longer durations. Rubber padded materials provided consistent stress reduction, while Ogden 2 and 6-parameter materials had the highest reduction in early milliseconds. The Kevlar based composite and Ogden material showed the highest reduction at the higher impact rates.

There are some points that are worth mentioning first is with increasing impact velocities efficiency of the helmet decreases which can be seen in all the provided tables, second at high stress helmets with padding layer are performing better than the convention ones.

Overall, all materials reduced stress compared to the skull, with Ogden-based hyperelastic materials and Kevlar excelling in early milliseconds. Rubber padded and Ogden-based materials maintained consistent protection over time, while composite materials were most effective in long-duration impacts. These findings validate the selected materials' effectiveness and support the development of advanced helmets for improved head injury prevention.

5.2 Future Work

Traditional materials in bicycle and motorbike helmets offer some protection but come with significant limitations. EPS foam is disposable, ABS is prone to UV degradation, and modern synthetic reinforcements are costly. These drawbacks highlight the need for advanced materials that offer greater durability, resilience to multiple impacts, and cost efficiency. Future research in helmet design should focus on a variety of bio-inspired materials, like marine shells and animal exoskeletons, which are known for their impact resistance. Incorporating materials such as graphene could further enhance protective capabilities. Advanced techniques like multi-scale modeling and machine learning could refine simulations and optimize designs for different impact scenarios. Real-world testing is essential to validate designs, while collaboration with various organizations can offer practical insights. Implementing smart materials and sensors can improve safety by monitoring helmet integrity in real-time. Sustainability should be considered by using biodegradable materials and sustainable manufacturing processes. Personalized designs, aided by 3D scanning and printing, can offer better protection and comfort. Long-term and multi-impact studies are crucial to ensure helmets remain effective over time. Integrating advanced materials such as ABS, Kevlar, and EPS foam can improve helmet performance and safety in high-risk activities.

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