Effects of Accelerated Ageing of Ballistic Composites on Impact Behavior

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DECLARATION

It is hereby solemnly declared that the whole work in this project report of “Effects of Accelerated Ageing of Ballistic Composites on Impact Behavior”, which is submitted to National University of Sciences and Technology (NUST)’s affiliated institution, College of Electrical & Mechanical Engineering, is based upon the work carried out by us after the proper literature review of books and under the supervision of our supervisor and co-supervisor. I further certify that no piece of this work is presented in any other Project Thesis or Report of any degree program in any university of the world. If any plagiarism from the students’ papers regarding the technical work is found then we solemnly are ready to face the consequences.

Language Correctness Certificate

It is solemnly certified that this thesis has been properly read by a linguistics expert and is free from any kind of grammatical, typing, semantic, syntax, and spelling errors. Also this thesis is in accordance with the guidelines and formatting provided by the university.

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ACKNOWLEDGEMENTS

The working over the thesis opens the creative minds of the students which lets them think outside the box and the regular studies. The postgraduate studies provide deep knowledge of the respective field and provide a thorough go through of the field and let the students discover their new set of skills. It requires a great determination from the students' side and great guidance from the mentors. In this journey of a few years of the postgraduate program and the thesis, a number of people helped me to get through my goals; who continuously encouraged me to achieve my goals and provided me guidance through all my way. With their help, I am able to accomplish this piece of work, for which we would like to pay our gratitude to them:

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Dedicated to my exceptional parents, lovely siblings, beloved wife, wonderful daughters and my dearest friends whose tremendous support and cooperation led me to this wonderful accomplishment

ABSTRACT

Military personnel, Law enforcement agencies, and Individuals employed on security duties require the highest level of protection when dealing with the lethal physical, chemical, and biological threats. Protective gears requirement is increasingly focused on ballistic protection level, anti-stabbing, and anti-biological protection. Ballistic effect onto woven flexible composites is a very complex problem given the structural binding of the materials, projectile’s impact velocity, material anisotropic behavior, and given boundary conditions. Ballistic products undergo degradation and disintegration with the passage of time due to actual operating conditions, usage, environmental conditions and storage techniques.

The main objective of this thesis is to forecast the strength and durability of the soft ballistic inserts which are made up of the fibers of “Ultra-High Molecular Weight Polyethylene” (UHMWPE). This study introduces a sequence of tests to determine the working life as well as to adapt to ballistic, physical, and mechanical properties resulting from rapid conditions of operation, by using composite ballistic inserts simulation. This research used data on the following ageing modeling techniques such as simulations for the ballistic inserts. The effect of mechanical loading and temperature cycling, as well as the solution simulating human transpiration, has been shown to affect and speed up the process of Polyethylene (PE) Depletion. Samples of Ballistic products were analyzed under specific conditions for 5, 7, 9, and 13 years in order to determine the connection and association between the normal ageing mechanism and the simulated ageing mechanism. In order to model and simulate ballistic impacts, ANSYS Workbench Explicit Dynamics (R1 2020) and SolidWorks (2018) were used. The simulation was based on systematic research by using the experimental approach and reference outcomes to evaluate composite armor ageing behavior.

Key words: bullet-proof vests, ballistic protection, accelerated ageing, the simulation of use, ultra-high molecular weight polyethylene.

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CHAPTER 1: INTRODUCTION

Ballistic products undergo gradual degradation, like any other product, with the passage of time and usage. Ageing is the mechanism in which changes in the material`s structure occurs as a consequence of the long-term effects of miscellaneous forces, contributing to the deterioration and disintegration of the substance. In such a process, irreversible changes arise in the substance and are primarily the outcome of the combined action of chemical reactions, external agents, oxidation (photo and thermo-oxidation) [29], cross-linking, deterioration, and eventually the decay and the disintegration of the component. Accelerated ageing is a process used to determine the life span of a product. The method is used for materials that retain their properties with no significant changes over long durations [5].

The main reasons for ageing and subsequent effects on the product are operating conditions, usage, and storage procedures. The ballistic substance property adjustment forecasts are related to safe use and construction reliability. The accelerated ageing process is used due to the long length of the evaluation. The most common expectation is that the changes induced by the ageing process result in the alteration of the structural properties and the physical properties (for instance, mechanical properties). But for its significance, the life cycle evaluation and ageing testing of ballistic items are given particular consideration.

Ultra-high Molecular weight Poly-Ethylene, also known by its acronym, i.e., UHMwPE, composite materials are commonly used for the manufacturing of ballistic body armors. An evaluation and review of this research indicates that the quantity of the variations produced by ageing of polyethylene plastic, on the basis of variations in mechanical and ballistic properties, has been determined.

1.1 Background

Ageing is a Degradation process in which a material loses its qualities over time. Usually, it is known that material is degraded when it fails to perform as per expectation during service life. However, this process starts with small changes in the material's physical and chemical structure. For example, changes in the crystallinity or bond-breaking are some of the slight degradation steps that take place at an early stage in the process and their effects are magnified with time and continuous exposure to the environment [24].

These fibers are characterized for having outstanding properties such as high elastic modulus, chemical and thermal resistance, and possess high crystallinity. All of these properties are attributed to their chemical composition and physical structure. Any alteration in the order of the composition and structure of the fibers may affect their chemical and mechanical properties. This implies that said changes affect the performance of the material, which sometimes results in loss of the mechanical properties and consequently, failure during service. This is of great concern for users of soft body armors since it represents a risk of death or serious injury. Chemical and physical factors in the environment such as high temperatures, humidity, low and high pH found in sweat, and wear can alter the material at the molecular level and display their effects as a reduction of the material's performance at larger scales [24]. Hence, studying the early stages of the degradation process of these high-performance fibers is important to predict and prevent their failure while in service. In the Figure 1.1, the effects of ageing are showed on the Kevlar [28].

Figure 1.1 Natural ageing effects on the Kevlar Polyaramide fiber (Picture courtesy Victor Hugo Cordeiro et al., 2019)

Kevlar and Twaron are the high-performance aramids; similarly, Spectra Dyneema fibers made up of Polyethylene are also high-performance Aramid fibers [6]. These fibers are commonly used as lightweight textile fabrics in military impact systems, for example, soft body armor 1 2 and the gas turbines. The cloth fabrics are often used as a backrest in a ceramic-struck armor device. Typical cloth armor is such a device that is prone to impact and some of the processes and deformation modes externally observed in the clothing. The standard range for armor supporters is the impact speed lower than the wave speed of the product. Therefore in this study, the impacts of the shock wave are not considered. The impact reaction also depends on projectile geometry, speed of impact, material activity, and limits. In general, the layers closest to the impact site experience local cross compression and shear, and the layers on the back are filled in flat stress [13].

1.2 Ballistic Impact Protection Materials

Soft body armoring solutions for ballistic protection has historically been created by means of layers of woven textiles stitched together; they now contain non-woven laminates, unidirectional layers, and tissue and non-woven laminates variations. With respect to the unidirectional strains, fibers are arranged in parallel in every unidirectional layer and stabilized with a polymer matrix or resin compatible like Kraton, which connects fibers. In very thin sheet shapes, the unidirectional layers are formed and stacked for example in zero degrees and ninety degrees cross-ply form. The layers are covered by adding Poly-Ethylene films and by applying thermal pressure the final laminated form is obtained. Figure 1.2 shows the thermal and oxidation age effects over the Polypropylene [14] [15] [16].

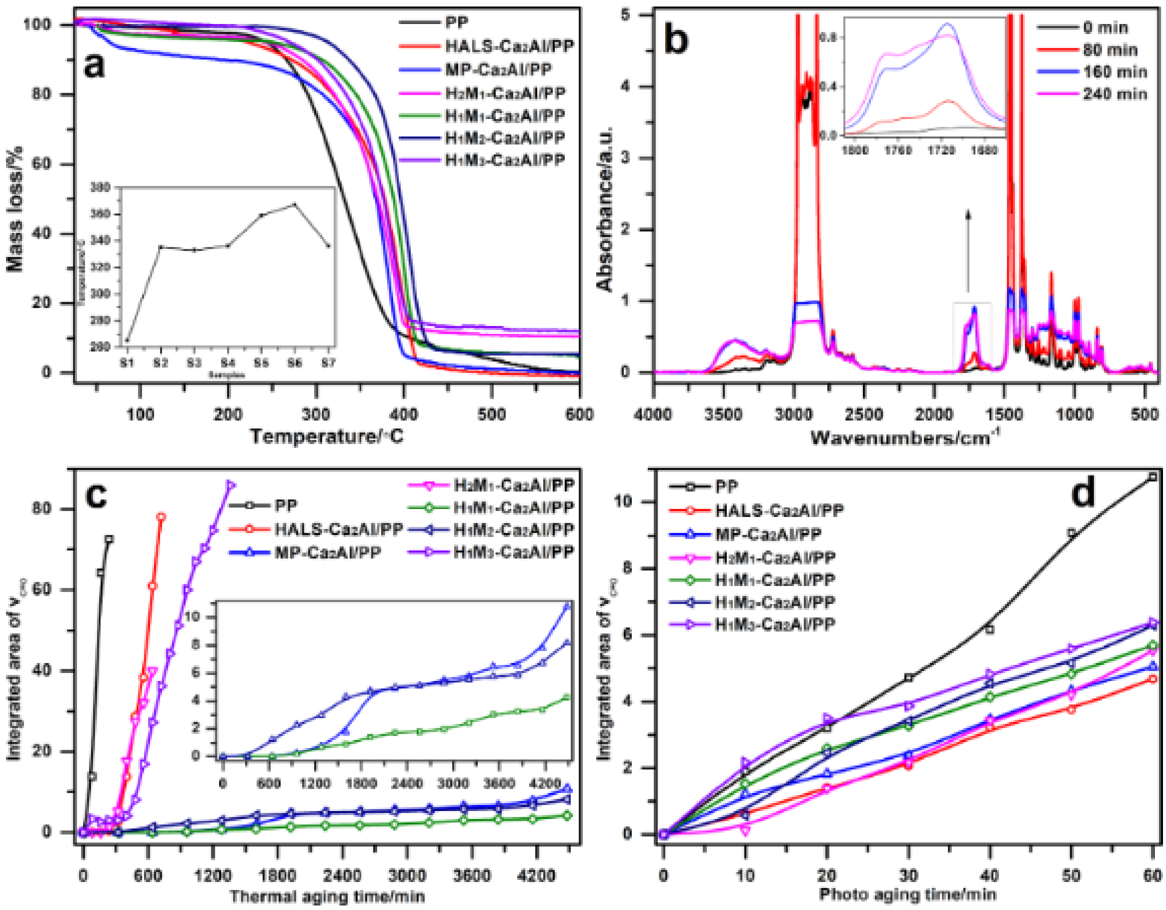

Figure 1.2 Thermal ageing and photo oxidation ageing in Polypropelyene (Picture courtesy Qain Zhang et. al. 2018)

Commercial unidirectional laminates are the Honeywell Spectra Shield (Ultra-high Molecular weight Poly-Ethylene Fibers (UHMwPE) and the Gold Shield (Kevlar) and the Dyneema DSM. The unidirectional laminates are often used for ballistic defense. Hard-textile or composite armors, like the helmets, are not versatile and specified as the fabrics are bound with a rigid resin material. The textiles armors of today, such as bullet-resistant jackets and helmet, are made up of many advanced, multi-dimensional polymeric fabrics and fiber manufacturing techniques [1].

1.3 Accelerated Ageing of Ballistic Material

Changes in the structural properties and the fundamental physical properties (for instance the mechanical properties) in the material are induced by the ageing process; and it is most commonly expected. Due to the importance of consumer protection, the assessment of the life cycle and the ageing testing for ballistic products and raw materials for ballistic items are becoming more and more relevant. UHMWPE (Ultra-high Molecular weight Poly-Ethylene) plastic sheets are one of the most extensively used components for the manufacture of our personal ballistic weapon. The methods of accelerated ageing of materials were used due to the long length of the natural ageing process. The findings obtained for further analyses based on chosen mathematical methods provide a foundation for ageing analysis that offers an accurate explanation of the ageing phenomenon. In order to ascertain the degree of improvement to those properties for a period of time than the assumed time of the study, a simulation of adjustments in the characteristics of the test component, performed by using chosen prediction methods is to be undertaken [17].

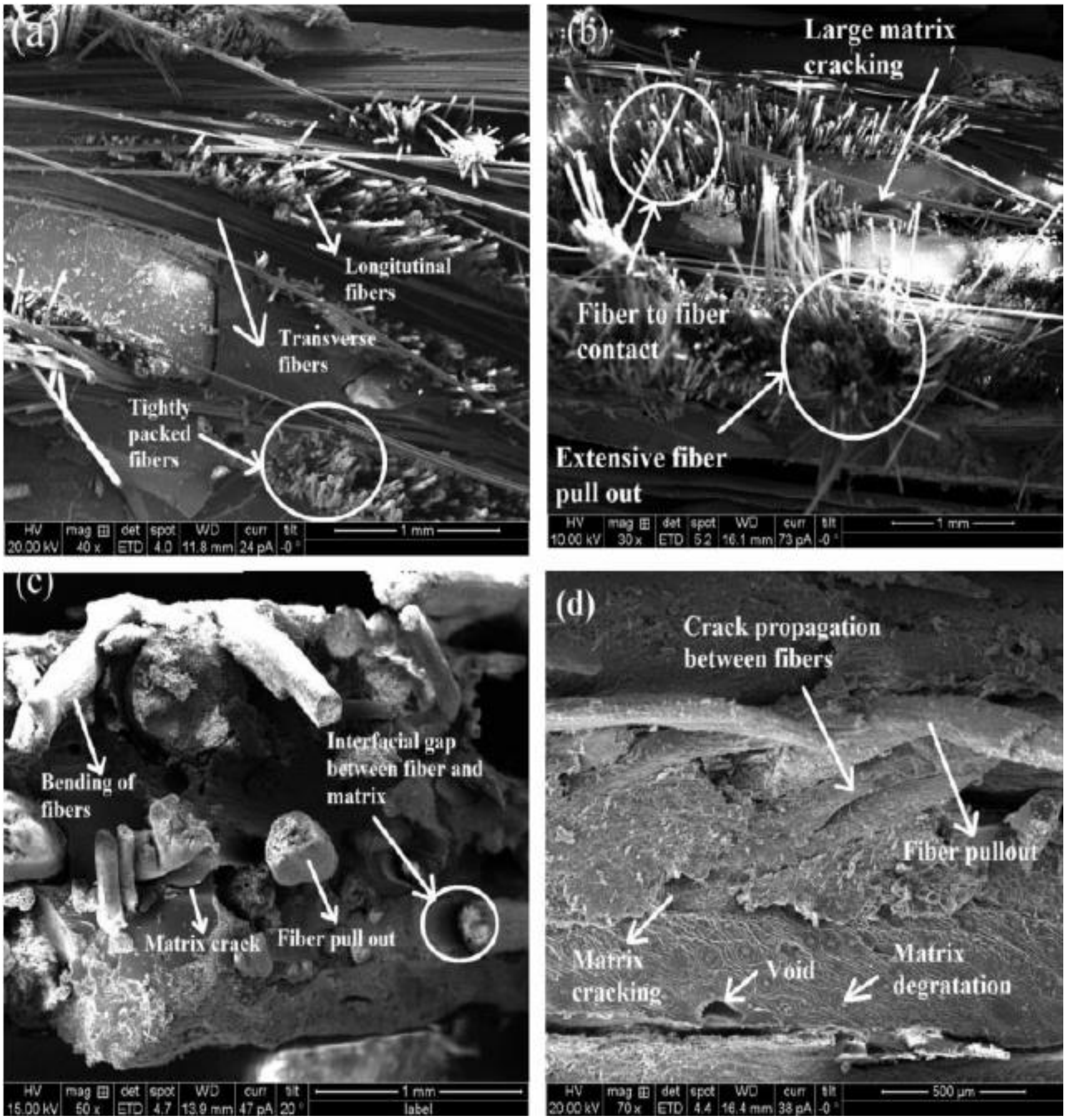

Figure 1.3 SEM Images of tensile fractured specimen of GM/UPR composites (Picture courtesy S. Kalirasu et al., 2015)

1.4 Effects of Accelerated Ageing on Ballistic Composites

As the ageing factors come into play, the modified textile composite characterized the influence of ambient environments, temperature, and humidity by their ultimate tensile strength. The longitudinal strength of the changed samples decreased during ageing cycles marginally lowered, and when temperature or the humidity were used as ageing influences, the unmodified textile composite's mechanical strength was significantly decreased after twenty-eight days of accelerated ageing [12]. The prolonged ageing of unmodified textiles (after twenty-eight days) resulted in a statistically significant reduction in stress power. For the elongation at full load, a related effect has also been noticed by many researchers [2].

1.5 Outlining the Thesis Report

The report of the thesis “Effects of Accelerated Ageing of Ballistic Composites on Impact Behavior” is divided into a number of chapters; each chapter provides a topic, upon which it discusses the literature and relevant details.

Chapter 1 briefly describes the ballistic materials, their degradation, and their relevant topics. This chapter provides the background study of this topic as to why this topic was selected at first and how the ageing of Ballistic Materials does is accelerated and what are its effects on the Ballistic Composites.

Chapter 2 describes the literature review that we have done and important parameters needed for understanding the need of body armor, the design criterion, the energy absorption based on the impact, the performance evaluation of ballistics, the standards of body armors, impulse and energy relation, and the description of bullet resistance etc.

Chapter 3 focuses on the methodology; it provides an overview of how the ageing process happens and accelerates. Then what are the experimental parameters that are going to be watched. Apart from this, the selection of materials and the respective ageing methodology and the ballistic properties of that material will be assessed.

Chapter 4 presents the mechanical design and the material properties used for the ballistics armor. Along with the modeling, another feature of this chapter is the simulation.

Chapter 5 provides the results and discussions; showing that what is the impact of ballistics on Standard Dyneema and under different conditions of temperature and humidity.

Finally, the last section that is the **Chapter 6** includes a conclusion and a few future work recommendations that how in future students may carry upon my work.

CHAPTER 2: LITERATURE REVIEW

The history of mankind is distinguished by the relentless fight of human for the survival; which means that he has to conquer or overthrow what threatens the human existence: for instance natural catastrophes, aggressive animals, and others. The defense of proximal risks, versatility to escape combat and defensive clothes and gadgets for direct contact with the enemy is pursued, depending on their threat. This research examines only one aspect of the human survival initiative – protective gear. This study focuses primarily on the nature, components, and testing of durable fabric apparel, in which soft body armor is used to defend ballistic objects.

2.1 Body Armor

Modern age production of body armor to shield against possible bullets and high speed projectiles or fragment pieces began with the Korean War; which provided much needed impetus for modern scientific research in this field. In the contemporary armies of the world, the principal forms of armor include ceramic 'rigid' armoring plates, versatile armors, and ' soft sensitive' armors [26].

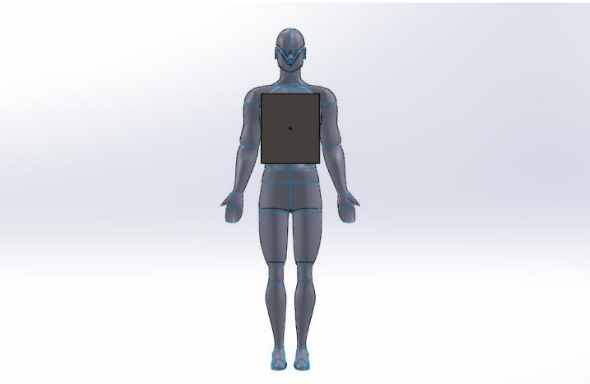

Figure 2.1 Ballistic Protection offered by body armor against bullets (Front View)

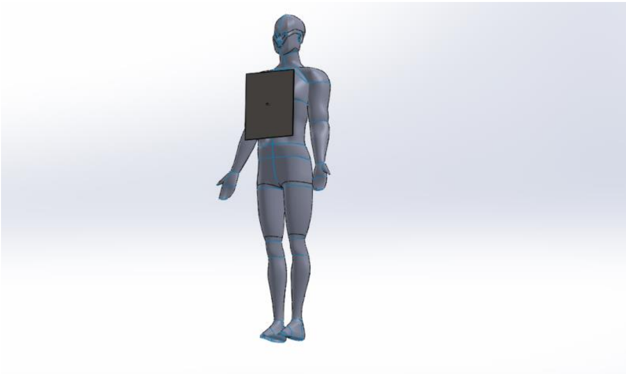

Figure 2.2 Ballistic Protection offered by body armor against bullets (Transverse View)

The versatile shield mostly consists of Aramid layers and/or nylon that dispel the kinetic force of the projectile by expanding fibers (so-called low energy bullets or shards). Originally developed by a US corporation named DuPont to replace steel belting in car tires, a Kevlar form of Aramid Fiber was recognized by the United States National Institute of Justice's (NIJ) Research division as a substitute to nylon in personal armors [9]. It was clear that nylon was superior and is now omnipresent. Typically there are three components of Rigid plates: a hard ceramic blow face that is a bullet eroder and a dissipater of energy, ceramic energy absorbing support (typically aramid composite), and a handle that connects all of those materials. INIBA plates, which are Improved Northern Ireland Body Armor in Northern Ireland, consisting of alumina ceramic (Al2O3) that can overcome rounds of 7.62 mm.

2.2 Design Criterion

In order to be safe from ever present risk, body armors should always be worn. The armors must conform to the requirement of the user, correctly spread their weight around the body in order to reduce user fatigue, have adequate breathing strength for long use particularly in high temperature, and cannot barge into with, or impair, the mobility of the user. The essential challenge is to balance it against the weight, comfort, and versatility, expense, and environmental exposure (moisture, light, heat, and ultraviolet, etc.) and service life the level of protection needed by unique type(s) of hazard.

Figure 2.3 Body armor parts design (Picture courtesy Yuku Yoneda, Eco textile and under design)

2.2.1 Energy Absorption Based Upon Impact and Residual Velocity

A ballistic efficiency of a fabric is determined most specifically by its absorption of energy. The equation given as follows has been used by many researchers:

$$\Delta E = \frac{1}{2} m (v_s^2 - v_r^2)$$

Here in this equation, ΔE is the kinetic projectile energy loss in Joules; "m" is projectile mass in kilograms, v_S & v_r are respectively hitting and residual projectile speeds in m/s.

V_{50} is characterized by the average of the highest partial penetration speeds and lowest full penetration speeds in a given speed range. This V_{50} can be accomplished by at least two partial speeds and two full speeds of penetration. There are commonly seen 4, 6, and 10 rounds. Many researchers have normalized the absorption of energy from the fiber by separating (v_{s2}-v_{r2}) by v_{s2}, as opposed to V_{50}. The energy consumed was seen to be proportionate to the strike speed and the armor system's areal density. With a Fragment Simulated Projectile (FSP), the V_{50} of different Ultra High Molecular Weight Polyethylene woven fabrics were tested by researchers. This data was used to study the structural effect of tissue over the ballistic performance. Young and Price have developed body armor systems that consist of various kinds of materials and use V_{50}. Similarly, a new ballistic performance indicator metric called BPI has also been developed, and the data for five Kevlar materials are measured against real V50 values. The satin fabric has shown that its higher lateral mobility offers ballistic efficiency over other materials.

2.2.2 Evaluation of Ballistic Performance based upon Back Face Signature (BFS)

The non-penetration test of the armor performance assessment is based upon the calculation of the back-face signature depression on the backing clay; it is one of the most common norms in the United States of America's National Institute of Justice. It has been implemented by various countries around the world since its first implementation in the year 2000. This standardization lists the efficiency criterion and the evaluation procedure for ballistic impact safety for the human body. Seven tiers of the ballistic armor are graded. The defense of Form I, II-A, II, and III-A against handgun threatening is rising. For use in a tactical scenario only Type III and IV armor; this defends from high-intensity rifle round. Table 5.1 indicates the norm as indicated by the National Institute of Justice. The supporting material in use is a form of clay, Plastilina; and the two chronographs describe the velocity of this projectile as presented in Figure 2.1. To complete the exam, forty-eight rounds are fired. There is no approval for penetration. 16 steps will be reported at standard obliquity and no rear signature depth is permitted to exceed 44mm.

2.3 Body Armor Standards for Military and Law Enforcement Agencies

Present the human body armors are being used for the ballistic protection, which secures the trunk of the human body and extreme regions of the body; they are designed to ensure adequate durability and durability against ballistic and projectile attacks, along with stringent requirements and specifications. For instance, a "ballistic resistance of NIJ's standard 0101.06" is formulated by the National Institute of Justice (NIJ), in order to categorize ballistic risk, including projectile forms, size, and velocities; to set deformation limits; to establish sample conditioning protocols and to determine non-military body weapons checks, can be seen in Figure 2.1. Table 5.1 specifies the projectiles of the NIJ's standard 0101.06 type, speeds, and overall permissible back face signature (BFS), such as deformable, stainless steel core, elevated-hardness core, and armor-penetrating, etc. [25].

Checking of the recognition of soft armors specifies the speeds and angles of incidence at their ballistic limits on specified projectiles. Various ballistic boundary speeds, each with statistical value, are described. They include ballistic limits V0, V50, which V100 and are designated as the maximum speed at which there is no total penetration, the speed at which a fifty percent chances of full penetration will happen, and the minimum speed at which the hundred percent chances of full penetration will occur. A variety of bullets are being launched at different positions, of zero degrees (normal) and thirty degrees (oblique) angles of incidence and at seams at a particular distance from the edges. Ballistic testing is done both on the dry body and on the wet body Armors. Testing also showed that the ballistic maximum speeds are commensurate with the density of the areal weight of the fabrics.

The Military Standard MIL-STD-662F shall be used for ballistic testing of military armor for troops, vehicles, and other structures subject to ammunition with small arms. Fragment testing of military armor generated from fragmenting ammunition, including grenades and mortar projectiles, shall be carried out in accordance with the Standardization Agreement of the North Atlantic Treaty Organization (NATO) 2920 [25].

2.4 Description of Bullet Resistant and Soft Body Armors

Body armor jackets are often designed from thin, breathable outer shells of nylon or cotton, and are made of rigid packs or panels in carrier type (pockets). The ballistic packs are made of non-woven, woven and sometimes with mixed woven and non-woven fabrics and can avoid penetration by an appropriate number of layers in NIJ's Hazard Categories IIA, II, and IIIA. For instance, deformable bullets shot from the firearm can be prevented by twenty to thirty layers of cloth.

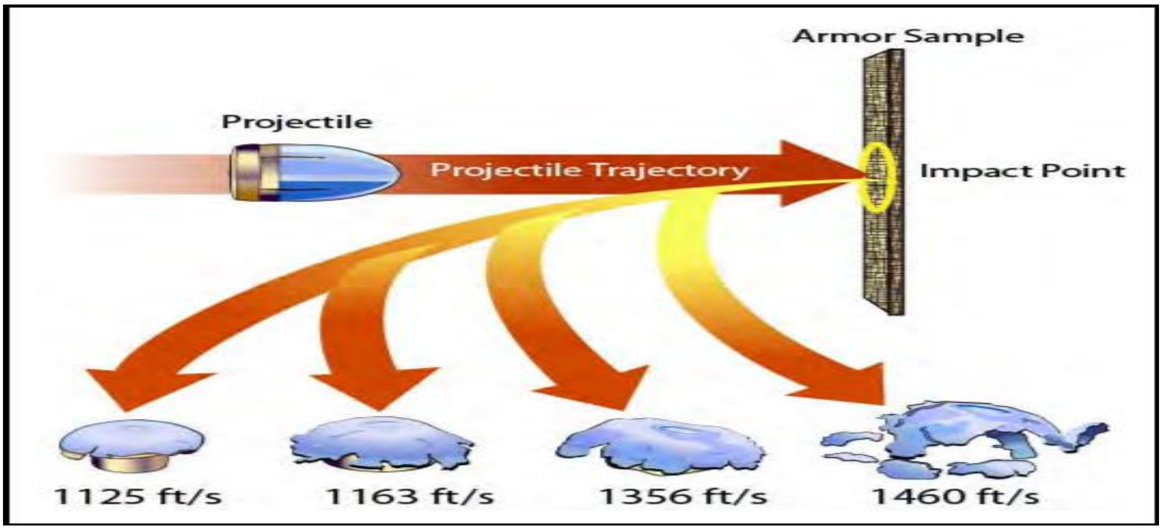

Figure 2.4 The formation of petal fractures in the caliber bullet and the blunting deformation (reproduced from Kungarani et al.) *[30]*

The blunt trauma’s additional protection is accomplished by attaching robust trauma plates to the armor's platform or inserts placed on vests' shelves, etc. However, intimidating stages III and IV are used to improve the speed and strength of weapons shot from cloth armor that can easily penetrate. The US Special Operations Command (USSOCOM)'s Special Ops Forces defend the military from such higher-speed attacks by providing rigid cover known as SAPI, which is abbreviated as the “Small Arms Protocol Inserts” or strengthened as SAPI (ESAPI) cover (inserts made-up of Boron Carbide Ceramics), etc.; armors, such as IBA vests for military personnel and releasable body armor vests. These plates are mounted ahead of facing the different strike faces of the armed jackets or vests to cause the projectile to grind down (i.e., fracture) before penetration of the tissue to disperse the load into the shield.

2.5 Impulse Momentum and Energy Balance Equation

As explained and presented by Sir Isaac Newton, the fundamental laws of movement apply to everybody, which also include the interacting masses, forces and their impulses. Apart from these equations of motion, the laws of momentum, mass, and energy conservation offer the governing equations for the complete explanation of such type of interactions between masses. To find such equations, let us consider the equation of momentum and impulse, which is provided in terms of the following equation. It is quite helpful in this matter if the effect force F generated on the target by the projectile is used to describe the function of the change of linear momentum:

$$\int_{t_i}^{t_f} F\,dt = m(V - V_f)$$

When “F” is impact force, “t” is time, m is projectiles weight, “V_i” is the originally projectile speed, “V_f” the final projectile speed (V_f = 0 for non-penetrating impacts); where F is an impact force. The energy balance as an equation for a solid projectile (non-deformation) controls the effect case since energy is conserved if heat dissipation and acoustic energies are ignored and any kinetic rotational energy for the projectiles are reduced.

$$\frac{1}{2}m\left(v_i^2 - v_f^2\right) = E_{damping} + E_{elastic} + E_{plastic} + E_{friction} + E_{kinetic}$$

Here on the left hand side of the equation, the projectile’s kinetic energy is shown; whereas each word on the right hand side of the equation is a particular function of the absorption of energy absorption, which is given by the fabric as under consideration. $E_{damping}$ is the energy absorbed or dissipated because of the viscous damping effects; $E_{elastic}$ is the energy absorbed or dissipated from the elastic strain (retrievable), $E_{plastic}$ is the energy absorbed or dissipated from the stretch of the body unpto its plastic limit; $E_{friction}$ is energy absorbed or dissipated by friction produced in the crossover areas of thread, yarns and projectiles.

2.6 Ballistic Impact on Composites

In general, the ballistic impact is low in mass, the propellant source's high-speed effect. The ballistic limit of the target is specified as the maximum speed of a projectile where full drilling is done at zero escape speed.

During service life, composite systems are exposed to varying loads. The crucial prerequisite is to avoid the loading of external ballistic artifacts for the successful use of composites as defensive structures. For these applications, it is important to clearly understand the preconditions for penetration of the projectile into the composite target and the relevant harm mechanisms. A significant factor is also the residual strength after the ballistic effect. Includes damage loads in three categories: low-speed damage, high-speed impact, and hyper-speed impact. The explanation is that the flow of energy between the projectile and the target, energy dissipation, and processes for damage dissemination are experiencing dramatic changes as the speed of the projectile changes. One way to increase the ballistic threshold is to use woven composites [3].

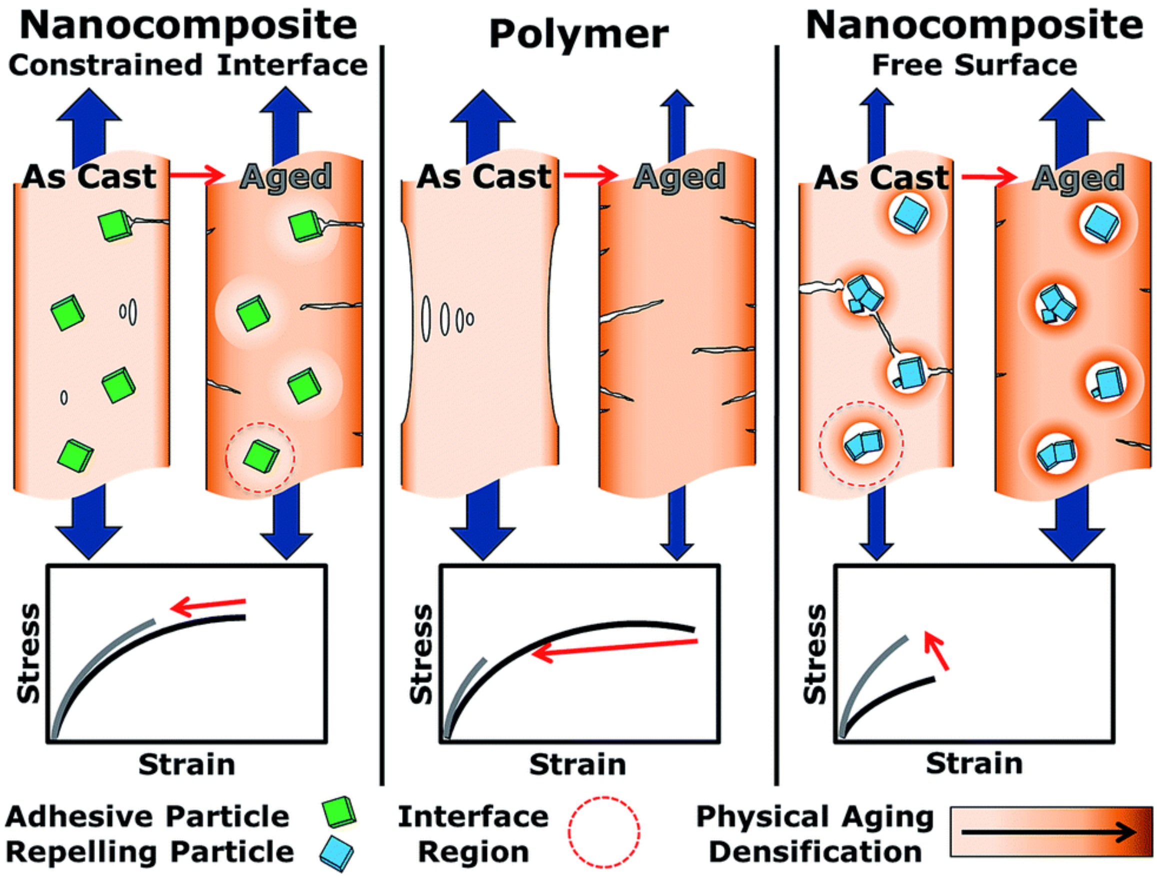

Figure 2.5 Physical ageing in nano composite films (picture courtesy Stefan J. D. Smith et al., 2016)

If the interaction interval is longer than the time duration of the lowest vibrational mode an impact occurrence would be called a low-speed effect. The supporting conditions are critical for low-speed impact regimes, as stress waves produced beyond the impact point have time to hit the edges of the structural unit, triggering their maximum vibrational reaction. On the other hand, the reactions of the structural system at high velocity or ballistic impacts are regulated by the 'local' activity of the material in the region surrounding the affected site, because the impact reaction of the system is usually autonomous. The time of interaction of the impacter is considerably shorter than the length of the structure's lowest vibration level. The hyper-speed effect requires missiles that travel at very high speeds, such that the local target materials are elastic and the effect pressures are also structural strength.

Some nuanced results in ballistic effects found in the webbing of a captured catcher's mitt are seen parallel to the loose woven body armors. Consider situations where a distortion-able projectile is deformed and the solid projectile has an effect, as seen in the semi-symmetrical models of Figure 2.2. Initially, the two bullets touch a minimum number of yarns, known as main yarns [11]. In the "via heavy," primary yarns tend to compress and tension waves cause them to dissipate energy from the impact site in both directions.

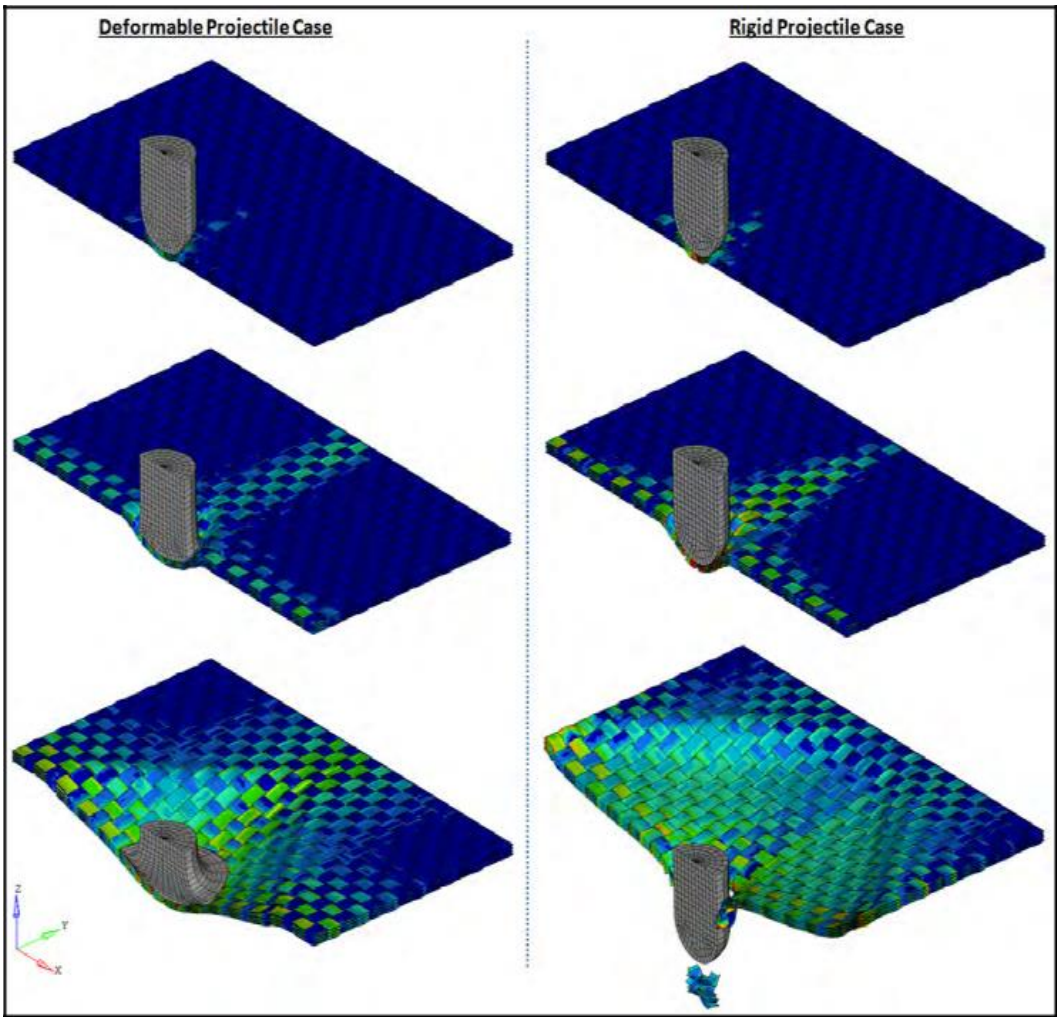

Figure 2.6 The Ballistic Impact over a Plain Woven Fabric which Shows Fabric Penetration Failure (Rigid Projectile Case), Projectile Blunting (Deformable Projectile Case), and Yarn Stress Wave Color Contours (reproduced from Kungarani et al.) *[30]*

However, the transverse zones redirect the energy back to the impact site - in contrast to unidirectional fabrics, a negative feature of the woven system. The primary yarns tend to deflect in the direction of projectile transportation from the cloth plane. These cross-waves are the unpredictable deflections, which can contribute to a yarn pull-out. It also allows the primary yarns to dislocate heavily from the path of the fabric. More basic yarns are increasingly employed, attempted to straighten them up (depending on the form of the projectile, thickness, stiffness, and yarn size).

CHAPTER 3: METHODOLOGY OF AGEING

3.1 Overview and Outline

To product some light weight body armors, a huge amount of efforts and a huge sum of money was spent and today we have body armors made up of fabrics, which have a high performance capability. The high-performance synthetic fibers exhibit superior mechanical properties which set them apart from other man-made fibers in industrial application. Materials not only provide high strength and tenacity, but even low weight is required for ballistic applications. Fibers that are most commonly used for soft body armor are predominantly Aramid and UHMWPE fibers. In contrast to other synthetic fibers, the strength is greater depending on weight and number.

A comparison with other materials is shown in Figure 3.1. PBO (Poly-phenylenebenzobisozazole) is a type of synthetic fiber that satisfies the physical requirements for ballistic applications. Nevertheless, it has been found that its exposure to moisture may result in the loosening of fiber morphology, leading to the degradation of physical properties [8]. Moreover, PBO shows worse tensile retention properties than Kevlar when exposed to sunlight simulated radiation. The frictions formed in crossover regions start to engage in the twelve secondary woven fabrics (those that are not directly in contact with projectiles) [4]. The interstice (the oblique susceptibility region that is seen in the woven fabric, shown in figure 3.1) will extend and the slip between the families of the yarn will occur until crossover tension is over. The flashlights tend to slow down. The plastic deformable projectile (known as 'blunting') deforms with potential sites of fracturing. Blunting also causes a chest shaped appearance that raises the diameter of the tip of the bullet, allowing the number of primary threads to rise and the force of impact to be spread more broadly therefore the solid projectile does not deform. The impact force distribution resides as confined, resulting in an increased risk of tension failures in the primary strings. A peak flux is produced, which either completely arrests the projectile or helps it to penetrate, if enough primary yarn has failed. FSP results in single-layer woven fabrics in Figure 3.1 indicate thread defects and penetrations.

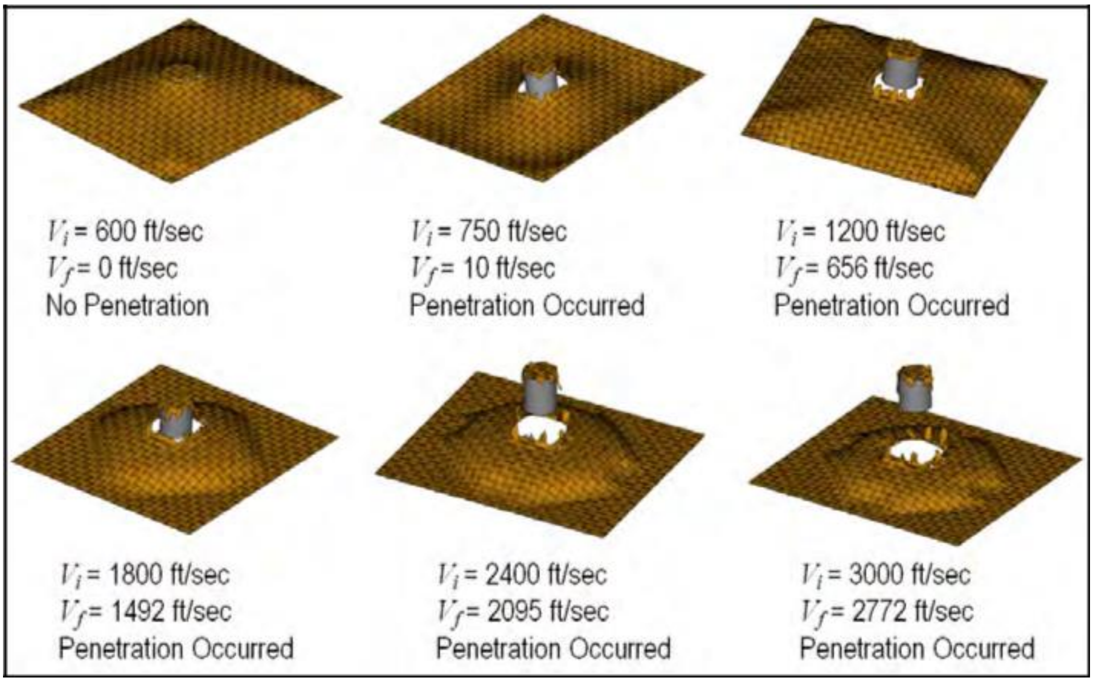

Figure 3.1 Two Grains Fragment Simulated Projectile Impacts over the Plain-Woven Fabrics (Numerical Models) which shows Yarn Failures and Transverse Waves for various Projectile Velocities (Reproduced from Ha-Minh et al.) [31]

3.2 Experimental Parameters

The end-users of bullet-proof and fragment-free vests made assumptions for this study, based on their risk perception and their feed-back, taking into account the aspects in which they can be used in practical terms. The simulation for the whole usage and utility of the caliber bullet and the bullet-proof vests was used in the study hypotheses. There are many fundamental reasons for improvements in the properties of ballistic body protection. The fundamental elements are listed here:

- Mechanical Fatigue occurring because of insertion deformations, friction between ballistic plates and exterior fabric layers, deformations which are induced by the logistics, i.e., the transport of the good and delivery etc.;
- Tiredness is induced by some foreign forces and effects such as dust and water, in the ballistic insert;
- Tiredness is caused by ballistic insert intrusion by immediate salt and moisture.

Considering the aforementioned factors, the software has been developed to investigate the usage of the insert over the soft ballistic. With the intention of modeling, the composite soft ballistic insert is usually used under some improvised ageing conditions; we had to select accurate, practical parameters of the simulated world.

For the simulation of ageing of the ballistic materials, data of the following three methods that can be applicable practically in this thesis was used:

1. **Method 1**: A mechanical load is applied in the insert;
2. **Method 2**: Add the mechanical load to the insert along with the temperature cycle;
3. **Method 3:** Adding mechanical load, along with the temperature effect and along with these two the effect of humidity can be catered for. Applying all of these together into the insert.

Testing of the ballistics inserts made-up of soft-composite Poly-ethylene Dyneema® SB-21 experimentally checked the methods. In addition, testing has been carried out using Snedecor's f-test. The study allowed the variations in the degree of impact of the factors of simulation used on the composite soft ballistic insert to be observed in the various procedures.

3.2.1 Mechanical Load Simulations

The ballistic wear was simulated on a fatigue test stand constructed by the team on mechanical deformation wear (cyclical local deformations arising from the configuration and behavior of a wearing agent) [10].

The measuring device was programmed by the entry into the control framework of the following parameters:

- Number of cycles between one and a hundred million;
- Single-cycle time may range from one to sixty seconds;
- Measure Angle from 10 degrees to 90 degrees (every 10 degrees).

A variety of tension loops were used in the exhaustion research program representing real-time usage. The ballistic jacket was intended to be used fifty-two weeks per year, including:

1. 3 days per single week (one hour of exercise);
2. 2 days per single week (six hours on the spot).

The above statement is that the Dyneema ® SB21 composite mechanical fatigue cycle has been defined by the number of deformation cycles in the fatigue testing station. On the testing station, the number of cycles can be defined as follows, taking into account a one year (N) period:

$$N = n \times k \quad (1)$$

"N" is here the number of deformation periods in comparison to the one year period participating on the fatigue examining station;

"n" implies a number of days in one year, i.e., thirty-three days, used for the sweater.

The deformation count, i.e. fifty is "k" per day.

Through the implementation of the following equation, the number of deformation periods on the station in comparison to the number of years used by the vest was calculated:

$$N = n \times k \times x \quad (2)$$

Now, here "x" is the simulated time of use, i.e., one to seven years.

3.2.2 Simulation of artificial human sweat's penetration into the ballistic insert

In compliance with PN-EN ISO-105-E04:2011, the simulation has been carried out for the penetration of human artificial transpiration into the ballistic insert [23].

The method of simulating the use of composite ballistic "warm" inserts consisted of immersing the test sample into the following solutions for a specified time:

- Alkaline medium, also known as the basic medium with a pH of 8 and above and pOH of 6 or below. It contains the following contents in 1 dm^3 volume:
  - **i.** 0.5 grams L-histidine hydrochloride ($C_6H_9O_2N_3 \cdot HCl \cdot H_2O$), (0.05%);
  - **ii.** 5 grams Sodium-Chloride, also known as Table Salt (NaCl), (0.5%);
  - **iii.** 2.5 grams of disodium hydrogen ortohophosphatedihydrate ($Na_2HPO_4.2H_2O$), (0.25%)
  - **iv.** Mixing all these three and filled with water to become a total of 1 dm^3;
- Acidic medium, also known by its pH of 6 or below and a pOH of 8 or above. It contains the following contents in 1 dm^3 volume:
  - **i.** 0.5 grams of L-Histidine hydrochloride ($C_6H_9O_2N_3 \cdot HCl \cdot H_2O$) (0.05%);
  - **ii.** 5 grams Sodium-Chloride, also known as Table Salt (NaCl), (0.5%); 2.2 grams of Sodium Dihydrogen-Orthophosphate Dihydrate

($NaH_2PO_4.2H_2O$) (0.22%) filled to **1**dm^3 volume with the water (distilled).

The simulation of usage involved immersing the entire ballistic implant into a solution that put on human sweat on the location where the test solution consisted of a 1:1 combination of alkaline (basic) and acidic sweat solutions. The test protocol consisted of absolute immersion, at room temperature and at 4 hours of incubation at a temperature of 37 ± 2 ° C in an oven, of the whole ballistic insert over a given time span (30, 60, 90, 120, 150, 180, and 210 minutes).

3.2.3 Thermal Shock Simulations

In compliance with methods of standard NO-06-A107:2005, fatigue simulation was conducted as a result of the cyclic shift in temperature. Samples were subject to three periods of temperature, each containing a temperature of:

-40±2°C for 2h

+50±2°C for 2h

The examination was performed in a climatic chamber of KBF-240 (BINDER-GmbH).

Fiber Types	**Fiber Categories**	**Density (g/cm^3)**	**Elastic Modulus (GPa)**	**Tensile Strength (MPa)**	**Strain to Failure (%)**
Glass	S-Glass	2.48	90	4400	5.7
	E-Glass	2.63	68.5	3500	4
Ceramic Fibers	Alumina (Nextel 3M)	250	152	1720	2.0
Carbon Fiber	Silicon Carbide	280	420	4000	0.6
	Standard	1.77	33.5	3651	1.5
	Celion	1.8	230	4000	1.8
Para-Aramid	Aksaca	1.78	240	4200	1.8
	Technora, Teijin	1.39	70	3000	4.4
	Twaron, Teijin	1.45	121	3100	2.0
	Kavlar 29, DuPont	1.44	70	2965	4.2
	Kavlar 129, DuPont	1.44	96	3390	3.5
	Kavlar 49, DuPont	1.44	113	2965	2.6

	Kavlar KM2, DuPont	1.44	70	3300	4.0
UHMWPE	Spectra 900, Honeywell	0.97	73	2400	2.8
	Spectra 1000, Honeywell	0.97	103	2830	2.8
	Spectra 2000, Honeywell	0.97	124	3340	3.0
Aromatic Polyester	Dyneema, Toyoba / DSM	0.97	87	2600	3.5
	Vectran	1.47	91	3200	3.0
	Zylon AS	1.54	180	5800	3.5
	Zylon HM	1.56	270	5800	2.5
	M5 (2001 Sample)	1.70	271	3960	1.4
	M5		450	9500	2.5

Table 3.1 The Specification of some basic High Strength/Modulus Fibers [27]

3.3 Material Selection

The aim of the study is to evaluate methods of predicting the life span/usable age of soft ballistic vest made of the composite that is based upon the UHMWPE fibers, which is abbreviated as Polyethylene Ultra High Molecular Weight Fibers. Ballistic protective products made of UHMWPE (Dyneema® SB21 /DSM /The Netherland) are used for testing and simulation. Dyneema® SB21 specifications are given in Table 3.2. Within the scope, ballistic protection product made of Dyneema® SB21 sheet, with dimensions of 30 × 36 cm having a width of 4.6mm was used. Moreover, samples were collected after five, seven, nine, and thirteen years, used in the routine condition.

Parameter	Measure unit	Value	Test method
Width	Centimeter	130.0±0.2	PN-EN ISO-2286-1:2000 [18]
Thickness	Millimeter	0.19±0.02	PN-EN ISO-2286-3:2000 [20]
Surface mass	gram/m^2	145.0±5	PN-EN ISO-2286-2:1999 [19]
Tensile strength			
Longitudinal direction	N	6 000 ± 500	PN-EN ISO 1421:2001 [21]
Transverse direction		5 500 ± 500	
Elongation at break			
Longitudinal direction	%	4.0 ± 0.5	PN-EN ISO 1421:2001 [21]
Transverse direction		3.5 ± 0.5	

Table 3.2 Parameters defined for the Dyneema ® SB-21 – Width is constant, i.e., 50±0.5mm and gauge length is constant 200±1mm (Reproduced from Fejdyś et. al) [32]

3.3 Ageing Methods

Variations in the properties of ballistic body inserts have few issues and causes which are stated below. Few are as under:

- Changes in mechanical properties because of the deformation of the product, friction induced among the ballistic insert and the fabric outside the ballistic vest, and finally the deformation because of the logistics department, i.e., transport and delivery of the product.
- Variations appearing due to external objects inside the ballistic vest, such as dust particles and moisture.
- Fatigue appearing due to the absorption of salt and moisture from human sweat into a ballistic insert.
- Variations in mechanical, structural, and chemical properties due to environmental effects
- **Method 1:** Application of mechanical load to the sample;
- **Method 2:** Application of mechanical load along with a temperature treatment to the sample;
- **Method 3:** Application of temperature treatment, mechanical load, and immersion in simulating human sweat solution to the sample.

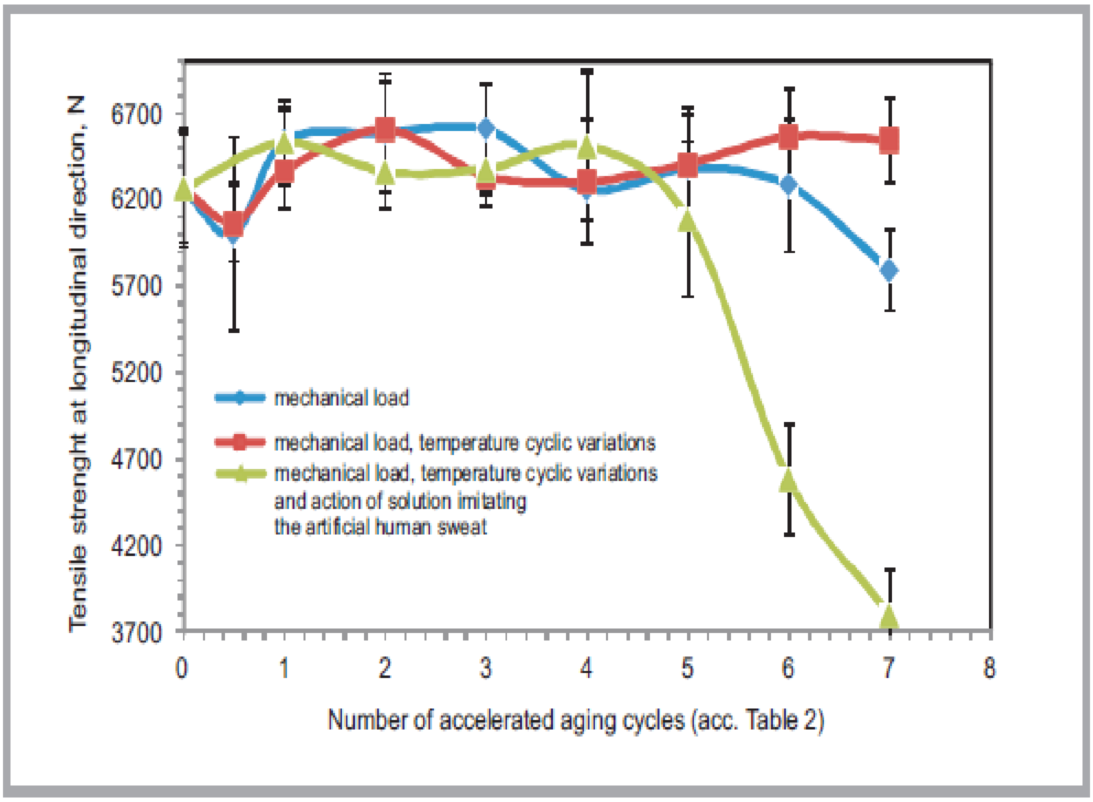

Figure 3.2 Dyneema® SB-21 is subjected to human sweat solution, temperature scale and the mechanical load, depending on the number of years of its breaking load (longitudinal direction) [Reproduced from Struszczyk et al.] [33]

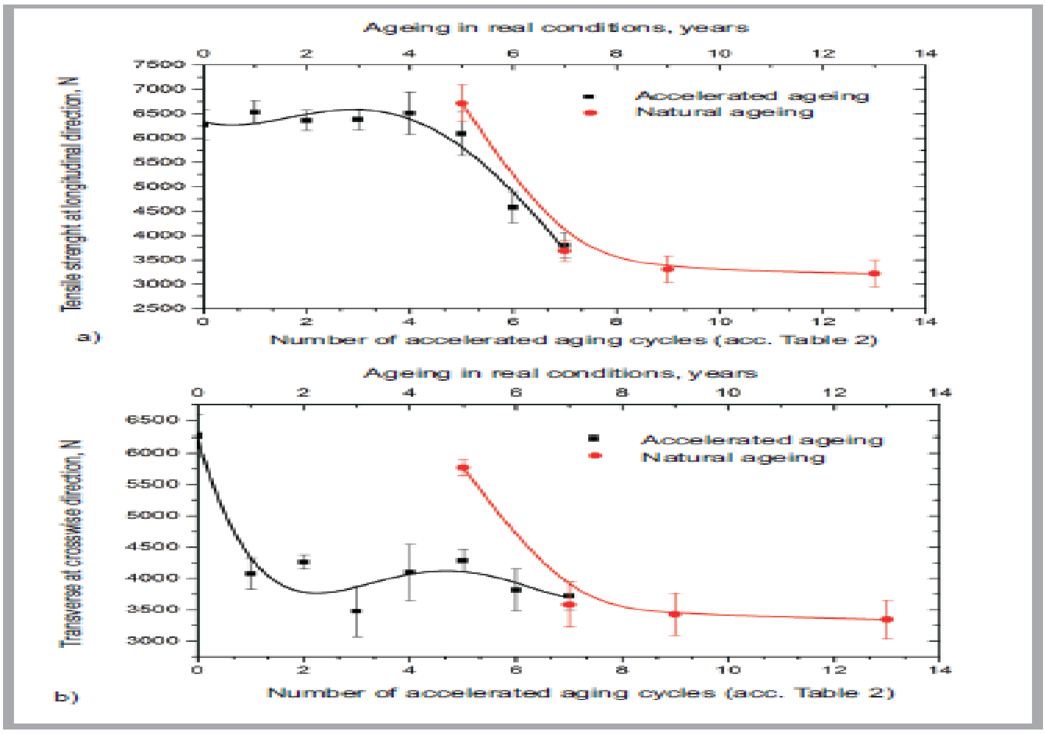

Figure 3.3 Effect of the duration of Dyneema® SB-21 inserts, and of those subject to the mechanical strain effects, cyclic fluctuations in temperature and solution simulate human sweat in longitudinal (a) and transverse (b) directions on tensile strength [Reproduced from Struszczyk et al.] [33]

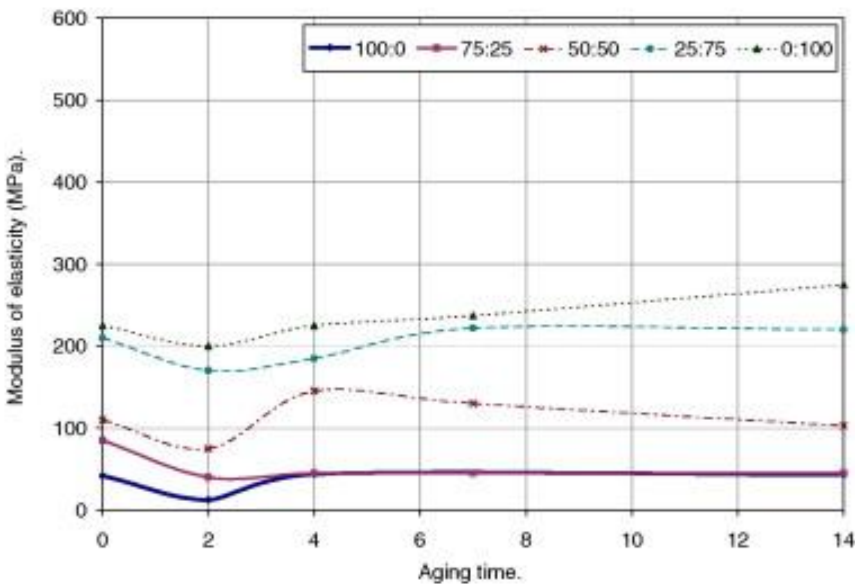

Figure 3.4The graph representing Modulus of Elasticity vs. the Ageing Time

3.5 Assessment of Ballistic Properties

Awareness of the mechanical properties of the fiber-based composite is important in order to understand its ballistic efficiency. The question is; mechanical composite characteristics are important for the ballistic impact process? It is not easy to answer the issue. The geometric scale for ballistic efficiency is difficult to assess. For the time being, one might presume that the fiber filament properties are important for the local penetration phase and the greater mechanical characteristics of the entire composite are significant for macroscopic incidents, such as the amount of deformation in the target back. Particularly essential are the tensile properties of the fiber and its composite.

With UHMWPE, the rope and elastics procedure or the tensile regeneration process was tested in the longitudinal compressive power of single fibers. It has also been calculated that the compressive force of the SK76 fibers using both methods and have recorded a compressive strength of approximately 880 MPa for the knot test and 340 MPa before the fiber localized shear deformation. They remember that for high-performance fibers the higher factor of 2.5 for the knot test is not unusual because the stress gradient operates both inside and outside of the ring. The compressive intensity of 90 MPa is substantially higher (Dyneema ® standard not specified) and it reveals how delicate this process is. The limiting factor is not compressive fiber resistance in composite applications, however, but macroscopic bending. A new collective Dyneema ® micro-buckling mode is recorded under macroscopic bending.

Dyneema® fibers can fibrillate under transverse compression due to the limited cross-sectional linkage of Van der Waals. The longitudinal load carrying capability is covered by this deformations mode. This property is useful in applications of ballistic defense because it guarantees the conservation of the fiber’s longitudinal strength under extremely high cross-pressures due to the impact of the bullet.

CHAPTER 4: MODELING AND IMPACT SIMULATION

4.1 Modeling

The sample of the armor is modeled with the help of ANSYS Workbench-(2020); the geometry of both projectiles i.e., 9 x 19 millimeter and 7.62 x 51 millimeter and sample was modeled with SolidWorks and then the simulation was finally done for the separate projectile; each varied ageing between [3, 5, 7, 9 and 13 years natural, artificial ageing] samples was done as per values of Figure 4.1, Figure 4.2, and Figure 4.3. ANSYS Explicit has been used to generate modeling and carry out ballistic impact tests. Modeling of each part has been done with keeping real values of armor and projectile.

4.2 Modeling of Bullets

The Parabellum 9 x 19 mm is a cartridge of gun that George Luger developed for the semi-automatic pistol named "Lugar", which is made by the German Firearms and ammunition manufacturer Deutsche Waffen-und Munitions-fabriken (DWM) and it was announced in 1902. In 2007, according to the report presented by the Newsweek "About sixty percent of the police used handguns are with 9 mm firearms cartridge", and credited 9 x 19 mm of Parabellum with making semiautomatic pistols more popular than revolvers. In the 2015 edition of Cartridges of the World, Parabellum 9 mm is "The most popular and most commonly produced military gun and sub-machine weapons ammunition". It may be due to the common belief that this device is efficacious for the use of the police and self-defense. Its low cost and wide availability lead to the continued success of the caliber.

The 7.62 mm caliber with a variety of cartridges is a nominal caliber. Historically this cartridge designation was usually used to describe a designation of full-power military rifle cartridges (MBR) and was classified as 0.30 caliber; an approximation to imperial units. The length is 0.30 inches, which can also be interpreted as three. It is also written in the form as: 3". The classification of 7.62 millimeter mentions the inner diameter of the ballistic caliber bullet on the field (it can be better anticipated as the rifled gun barrels' helical rims raised). The new caliber of the bullet is always 7.82 millimeter, while Soviet guns typically use a bullet of 7.91 millimeter when the old British (0.303British) and Japanese bullets are used.

The geometry of both projectiles was formed. Below are the inside and the outside of the bullet:

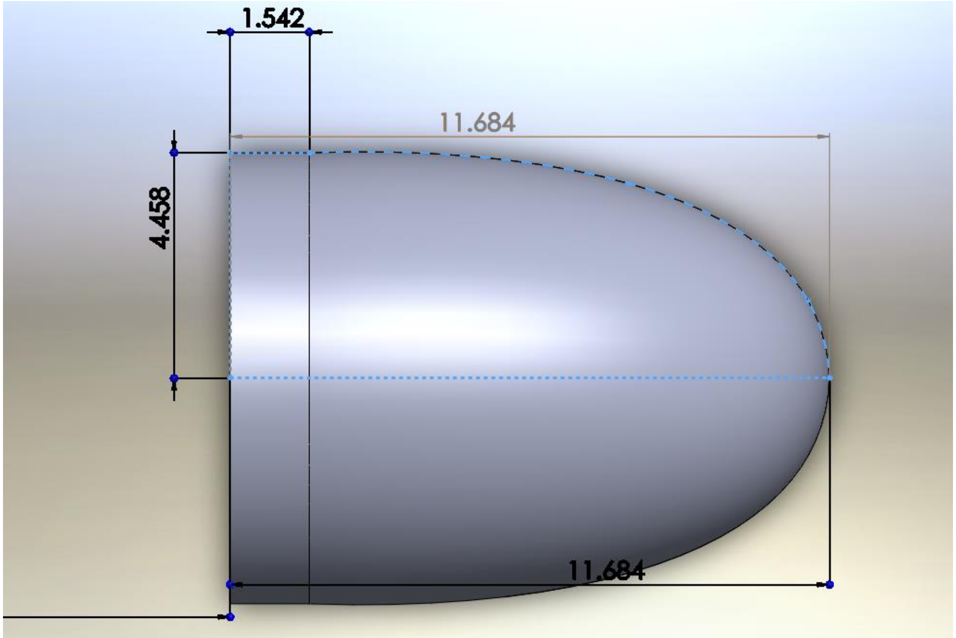

Figure 4.1 The representation of 9 x 19 mm bullet solid

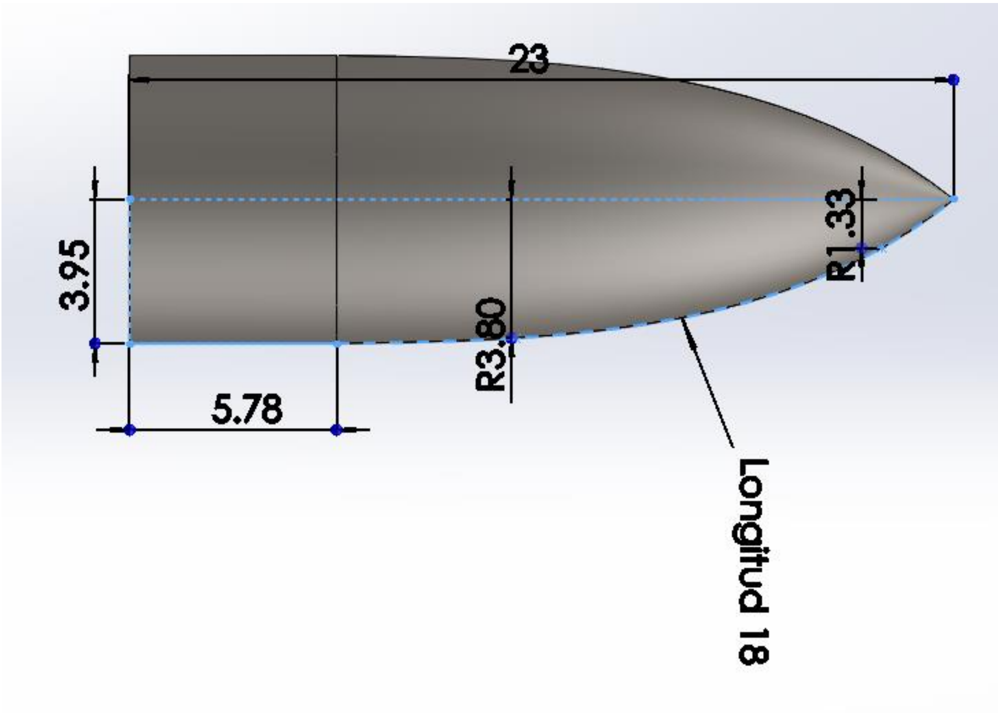

Figure 4.2 The representation of 7.62 x 51 mm bullet SolidWorks

4.3 Modeling of Ballistic Material

Dyneema SB21 composite material (properties are given in table 3.2) was modeled 30 x 36 cm sample having a width of 4.6 mm. 2 x Layers were meshed together as per the woven pattern of Dyneema SB21.

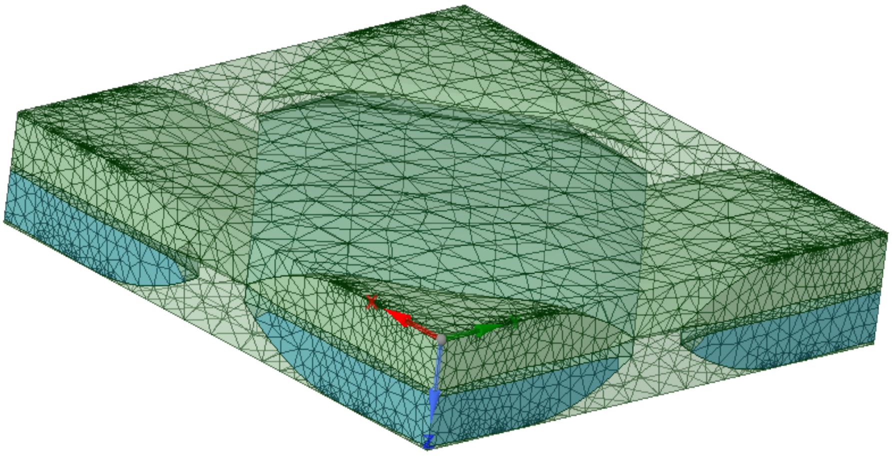

Figure 4.3 The representation Dyneema SB21 Composite Material Sample on SolidWorks

4.3.1 Ballistic Impact Simulations on Different Samples

The model has been solved in ANSYS AUTODYN 3D solver, initial conditions in the following order,

- Standard sample
- Aged under normal cyclic temperature condition and human sweat
- Aged Under 70 degree Celsius and 50% humidity condition
- Aged under 70 degree Celsius and 0% humidity

4.3.1 Impact Velocity

- Bullet 7.62 x 51 mm at 200 m as 650 m/s
- Bullet 9 x 19 mm at 25 m as 400 m/s

4.3.2 Bullet Weight

- Bullet 7.62 x 51 mm weighs 9.71 gm
- Bullet 9 x 19 mm weighs 7.97 gm

4.3.3 Impact Period

The impact period was adjusted as 0.001 sec and treating bullet as flexible and Dyneema ballistic insert as a rigid body for simulations under varying conditions and different aged sample values [7].

4.4 Simulations on ANSYS (based on results of Ageing Tests)

4.4.1 For 7.62 mm Bullet stress induced on material

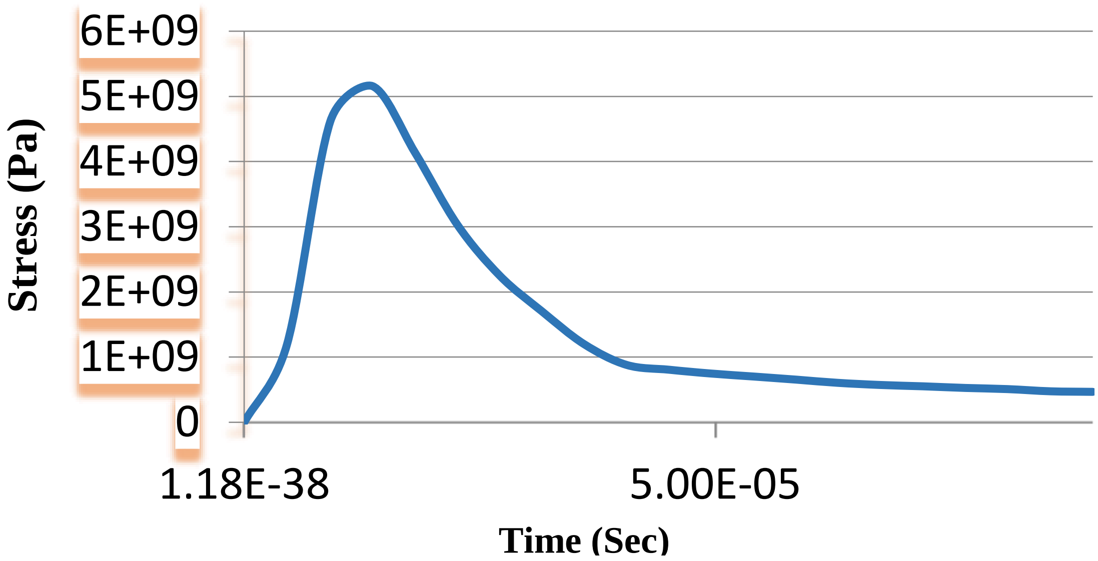

Figure 4.4 Bullet impact on 70^0 C and 0 % humidity aged sample of Dyneema

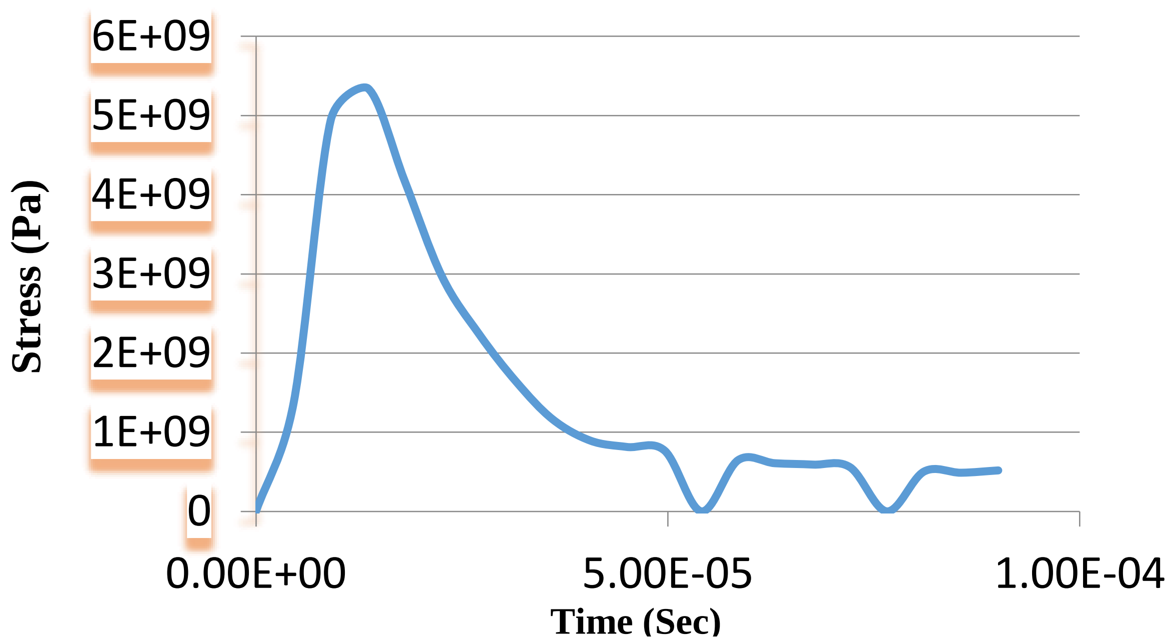

Figure 4.5 Bullet impact on 70^0 C and 50% humidity aged sample of Dyneema

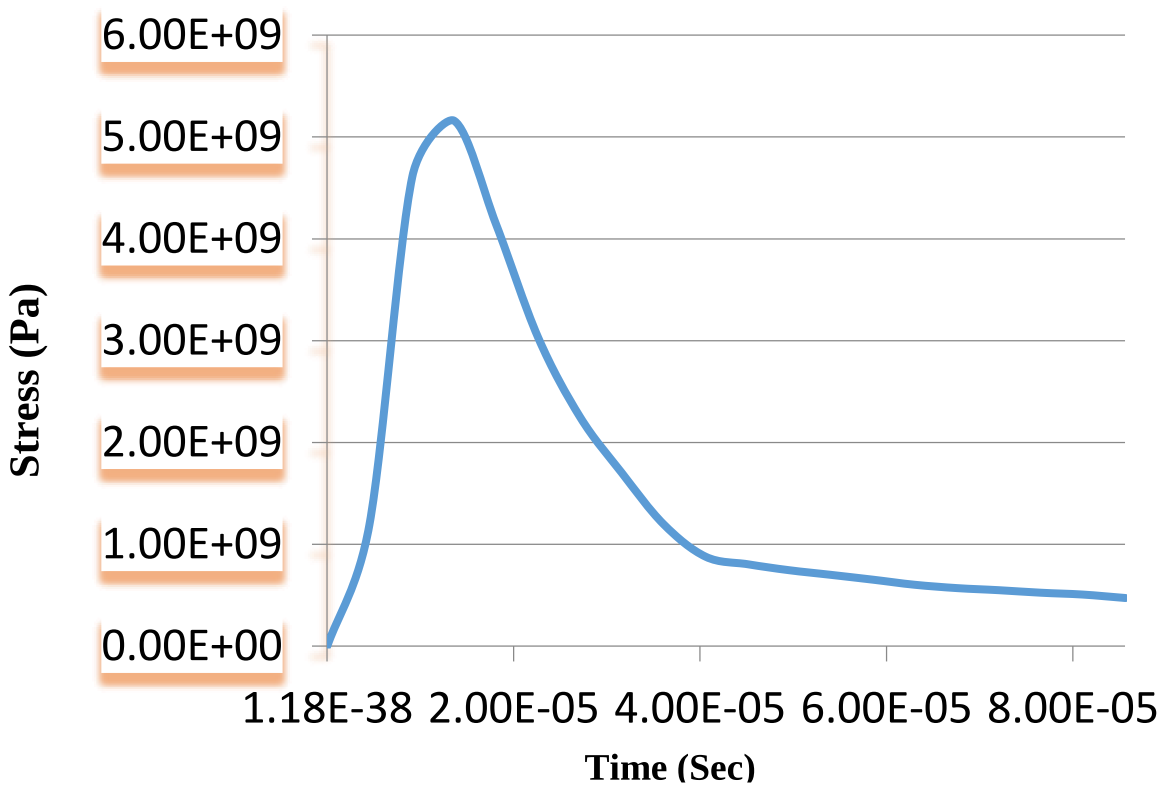

Figure 4.6 Bullet Impact on normal cyclic temperature variation and humidity aged sample of Dyneema

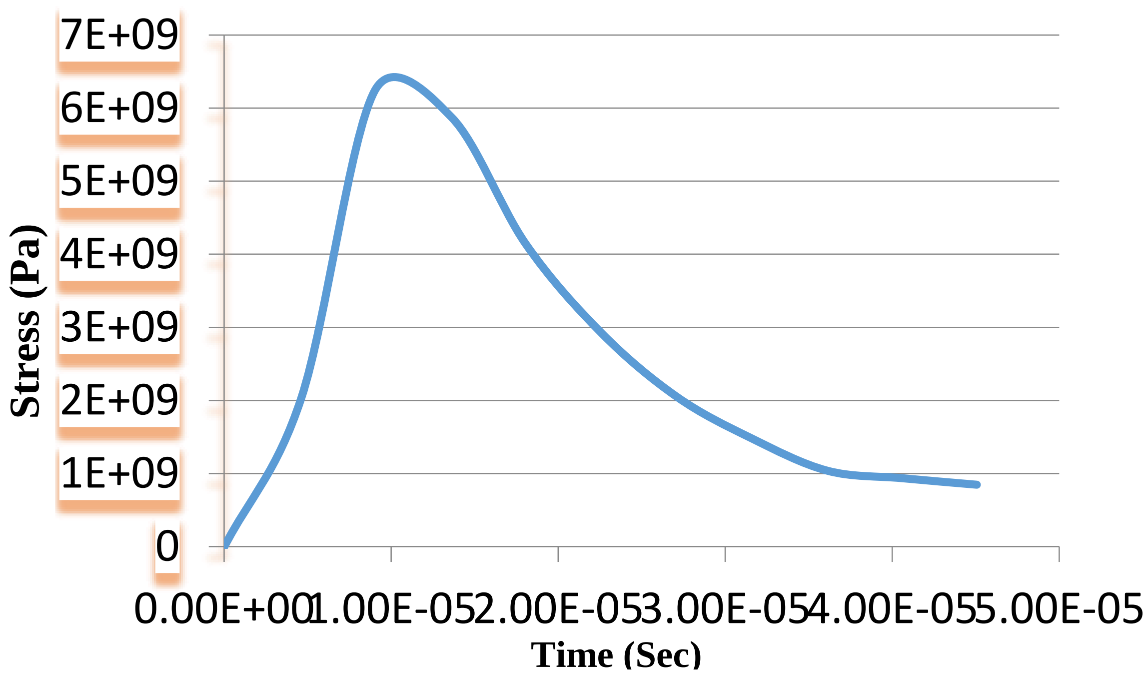

Figure 4.7 Impact of 7.62 mm Bullet on standard Dyneema

4.4.2 9 mm Bullet Stress induced on material

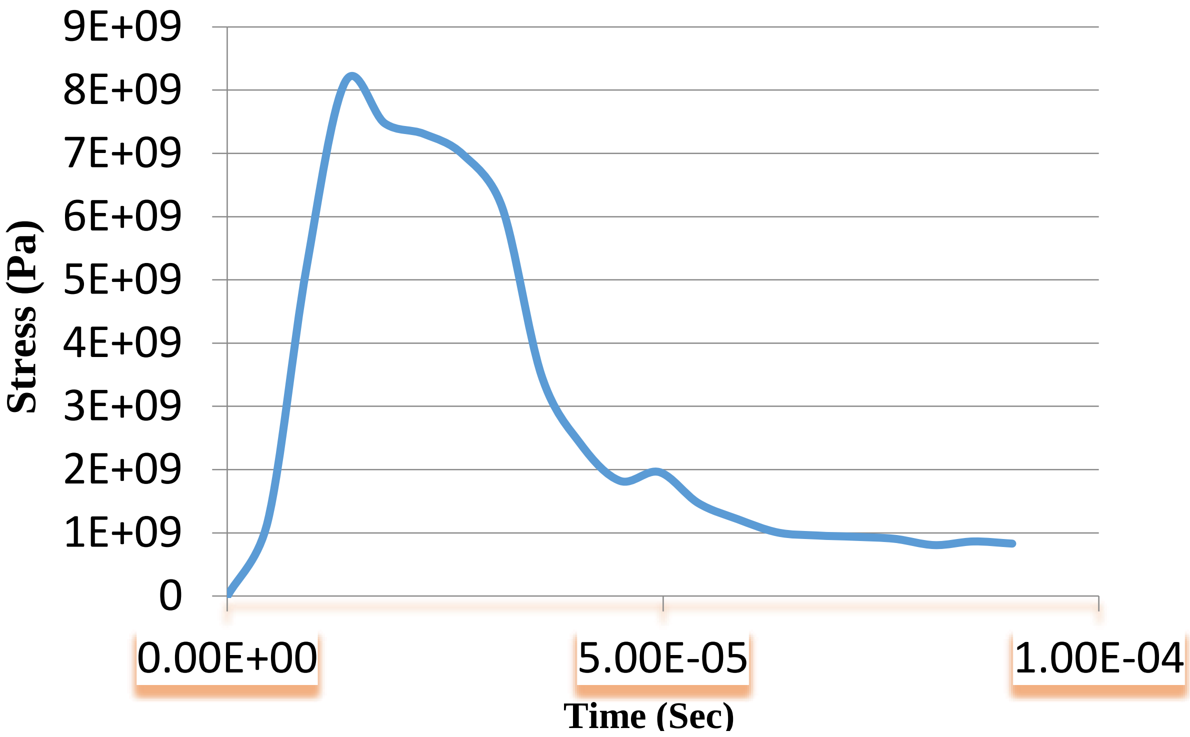

Figure 4.8 9 mm Bullet impact on 70 C and 0 % humidity sample of Dyneema

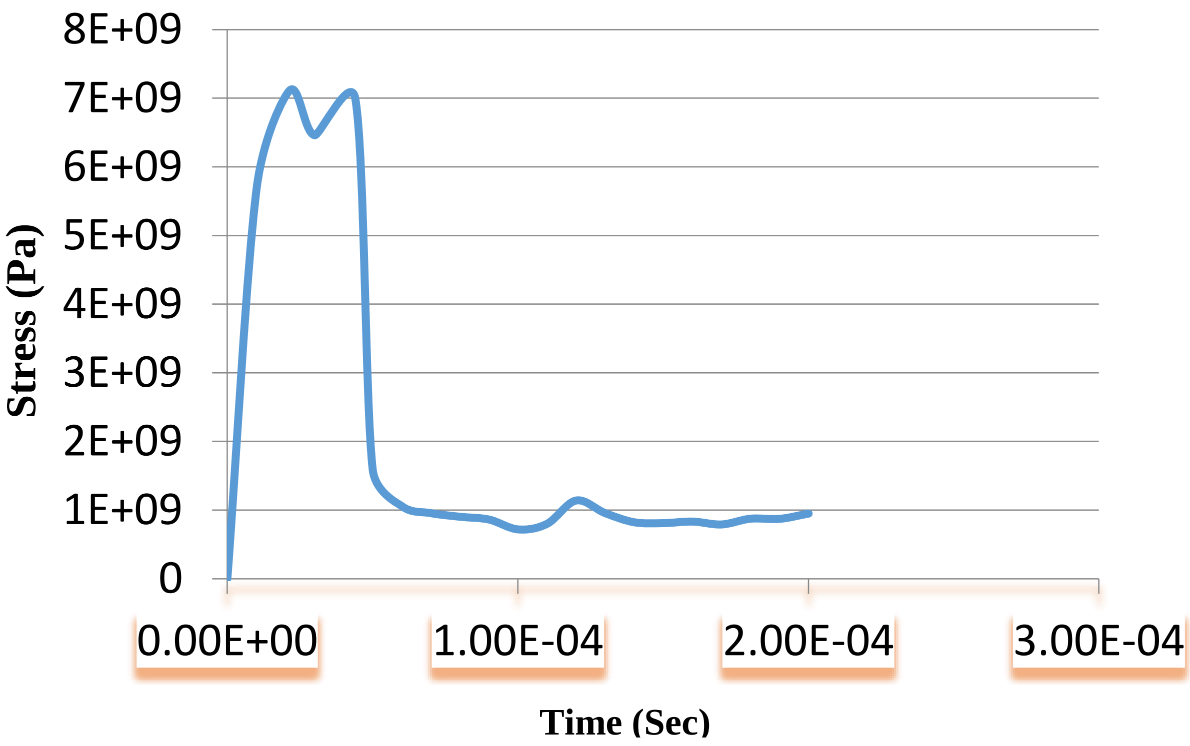

Figure 4.9 9 mm Bullet impact on 70^0 C and 50% humidity aged sample of Dyneema

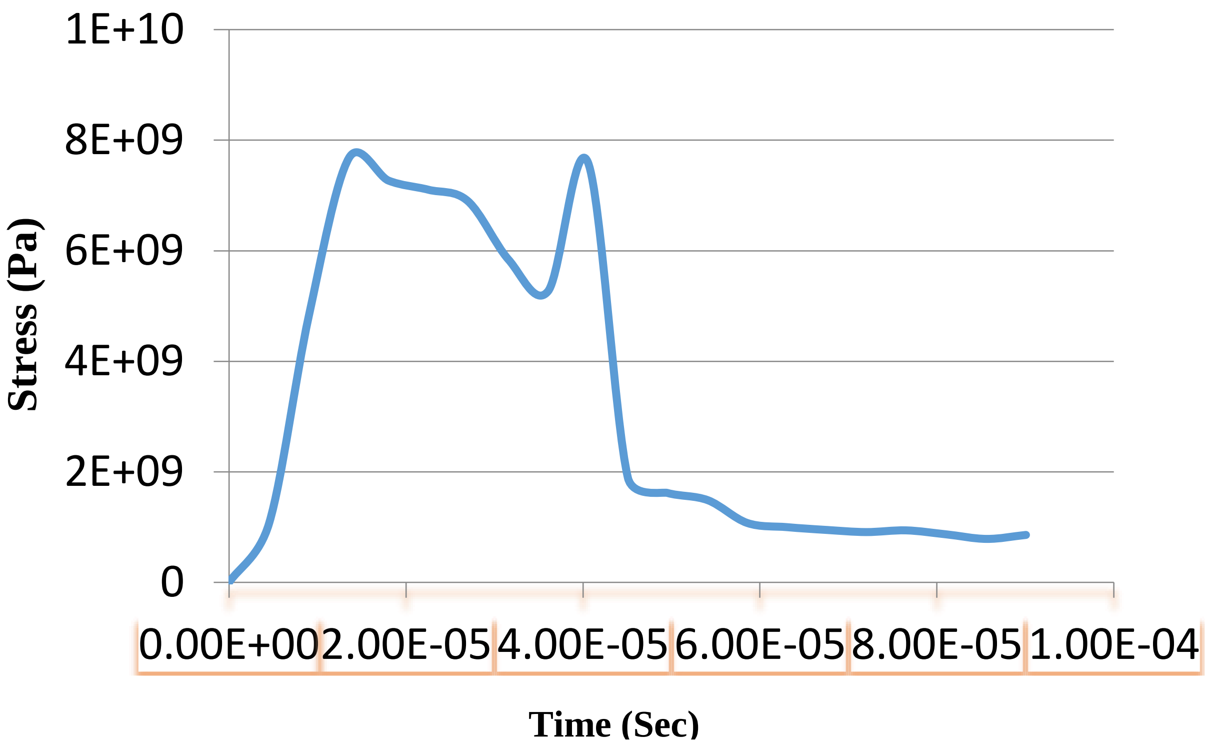

Figure 4.10 9 mm Bullet impact on normal cyclic temperature and humidity aged sample of Dyneema

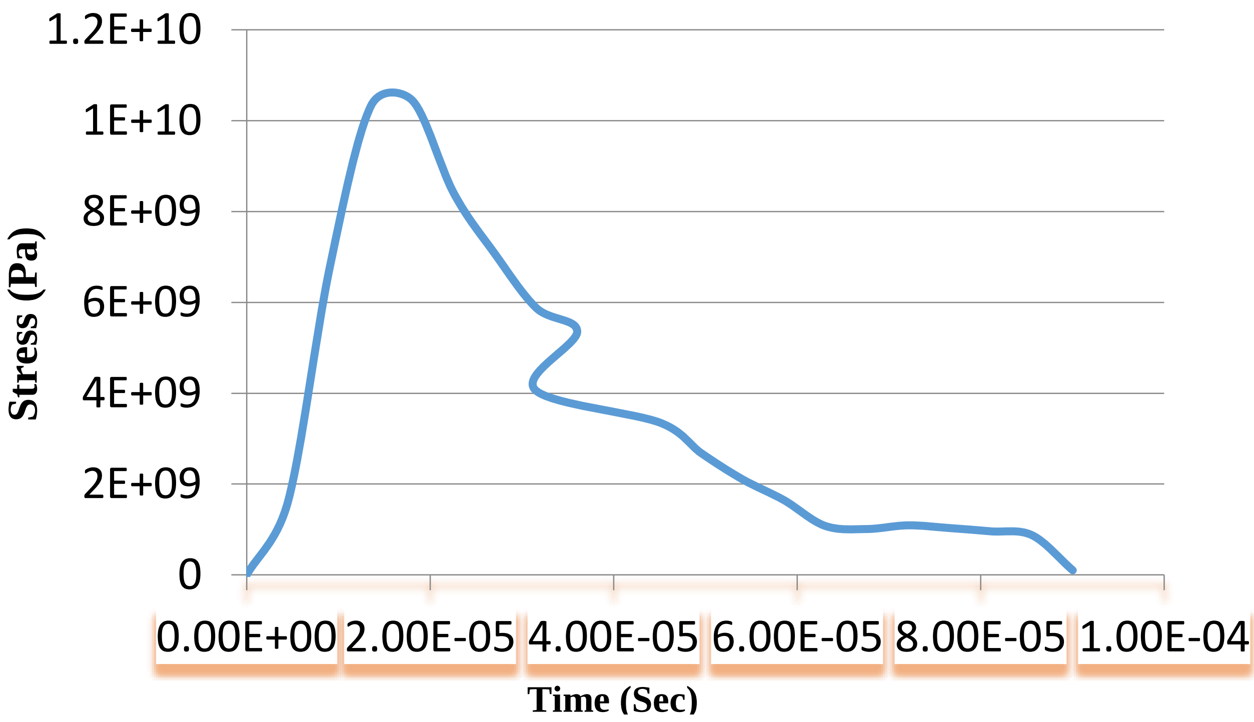

Figure 4.11 9mm Bullet standard Dyneema

4.4.3 Impact of Bullets on the composite material

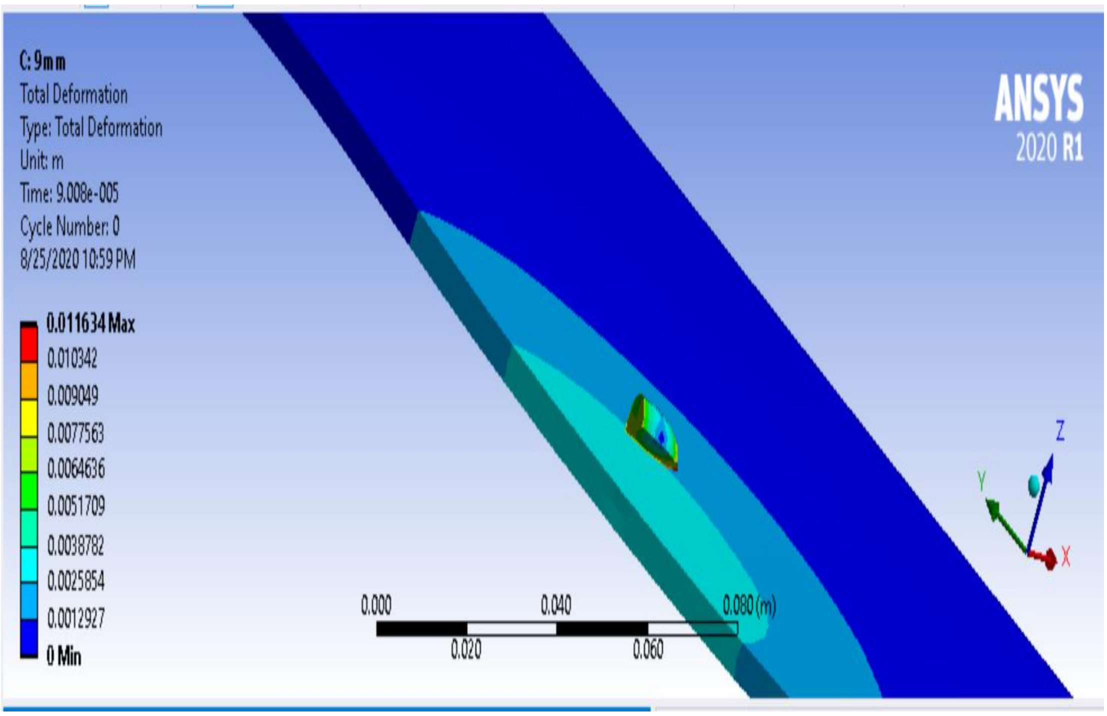

Figure 4.12 Impact of the 9 mm Bullet on the composite material

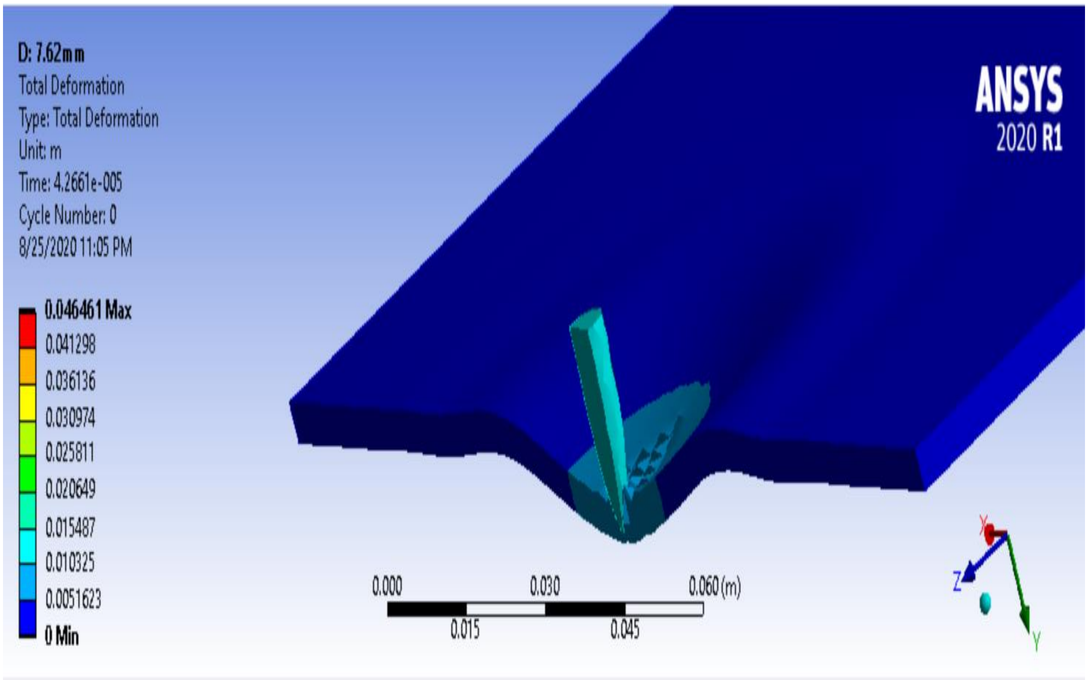

Figure 4.13 Impact of the 7.62 mm Bullet on the composite material

4.5 Results

There are different approaches and methods available to compare experimental and simulation ballistic data. Experimental data and simulation models both can be termed as good indicators for damage assessment of ballistic insert in terms of variations observed in shape, size, and structure of ballistic protective material. Ansys Explicit dynamic was used to solve simulation of ballistic impact against standard NATO caliber bullets of 7.62 x 51 mm and 9 x 19 mm. Procedure was repeated with both bullets against all four available aged sample Results of total deformation of samples, stress induced on samples and strain produced in samples due to bullet impact were calculated. Deformation and strain observed in samples were not as significant as stress bearing capacity of samples, primarily due to very less impact time selected. Simulation predicted prominent variations in stress bearing capacity of all accelerated aged samples in comparison with new standard Dyneema sample. Analyzing stress bearing of all samples and subsequent damage incurred onto samples due to ballistic impact on high speed bullets, it is evident that aged samples are more prone to failure.

Figure 4.8, 4.9 and 4.10 depicts that stress induced by standard NATO caliber bullet 9 x 19 millimeter against all aged samples (Sample aged under temperature cyclic treatment and 0 % humidity, sample aged under temperature cyclic treatment and 50% humidity and sample aged under normal cyclic temperature variation and immersion in solution simulating human sweat) was more prominent as compared to stress induced on similar samples by Standard NATO caliber 7.62 x 51 millimeter bullet. Analyzing graphs of stress induced on samples by ballistic impact of NATO caliber 9 x 19 millimeter bullet at the distance of 25 meter is very pronounced, which means all aged samples have relative lower strength and are more prone to penetration and ballistic failure as compared to standard Dyneema sample. Figure 7 depicts tensile strength variation in samples against a standard 7.62 x 51 mm NATO caliber bullet at a distance of 200 m. A new sample is relatively rigid and the bullet after impact is immediately deflected after striking the bulletproof vest, however, in all aged samples bullet after impact makes indentation and leaves after making ingress into samples.

CHAPTER 5: RESULT AND DISCUSSION

5.1 Mechanical Properties

Studying the mechanical properties of Dyneema® SB21 within the scope of this research, ballistic properties of package made out of Dyneema were evaluated. The simulation test included standard new sample and samples aged in accelerated conditions (ageing in the laboratory). Additionally, aged samples were observed and tested for results and variation in properties due to ageing methods for the numbers of years, i.e., [five, seven, nine, and thirteen years]. The variations and differences in properties of aged samples were again verified by:

- Effects of application of mechanical load,
- Effects of application of mechanical load and temperature treatment,
- Effects of application of mechanical load, temperature treatment and immersion of sample into solution simulating human sweat

Snedecor-F test was used to compare differences between the 1st and 2nd test procedures, as well as between the 2nd and 3rd procedure under normal usage. Experimental data, presented in **Table 5.1**, describes that the co-effect of the temperature cycle and treatment, immersion of sample into a simulating solution of the sweat of human, and mechanical load, reduces the strength properties of the Dyneema ® SB-21 composite sample significantly, same cannot be experienced without subjecting composite sample on to factors of fatigue used in method 2 and method 1. By evaluating the above-mentioned procedures of simulated aging the results were deduced; the estimated life or service life of the composite may be determined. Mechanical properties of the Dyneema® SB21 composite sample were evaluated against ballistic impact resistance in such a way that the service life curve may be established for the Dyneema® SB21. Such properties permitted us to regulate the critical or estimated numbers of cycles of fatigue, the cycles of temperature treatment, and the amount of time sample could be immersed into a solution simulating human sweat, after which a significant change in the properties can be experienced. During the experiment composite sample examined were visibly influenced and degradation was more pronounced in all three samples aged with different fatigue factors.

5.2 Ballistics Properties

The NIJ body armor standards ballistic measurements (see Table 5.1) show a decline in the impact of mechanical load, cyclic (-40 degrees Celsius, +50 degrees Celsius) temperature and miscellaneous ageing component, artificial human sweat, in the period of ageing over years. An intersection of results of different ageing mechanisms, such as cracking chains (which contributed to a decrease in V_{50}) or the forming of branches or crosslinking (increase in V_{50}) might have resulted in the above-mentioned phenomena. The finding of the simulation tests reveals that the tensile stress limit of the aged samples degraded by a total of 10% (after five, seven, nine and thirteen years), as opposed to the unused standard ballistic inserts.

Armor Type	Test Round	Test Bullet	Bullet Mass	Armor Test Velocity	Hits Per Panel at 0^0 Angle	Maximum Back Face Signature	Hits Per Panel at 30^0 - 45^0
IIA	1	9mm, FMJ RN	8.0 grams (124 gr)	373 m/sec (1224 ft/sec)	4	44mm (1.73 inches)	2
	2	.40, S&W FMJ	11.7 grams (180 gr)	352 m/sec (1155 ft/sec)	4	44mm (1.73 inches)	2
II	1	9mm, FMJ RN	8.0 grams (124 gr)	398 m/sec (1306 ft/sec)	4	44mm (1.73 inches)	2
	2	.357 Magnum, JSP	10.2 grams (158 gr)	436 m/sec (1430 ft/sec)	4	44mm (1.73 inches)	2
IIIA	1	.357 SIG FMJ FN	8.1 grams	448 m/sec	4	44mm (1.73	2

			(125 gr)	(1470 ft/sec)		inches)	
	2	.44 Magnum SJHP	15.6 grams (240 gr)	436 m/sec (1430 ft/sec)	4	44mm (1.73 inches)	2
III	1	7.62 mm NATO FMJ	9.6 grams (148 gr)	847 m/sec (2780 ft/sec)	6	44mm (1.73 inches)	0
IV	1	0.30 Caliber M2 AP	10.8 grams (166 gr)	878 m/sec (2880 ft/sec)	1 to 6	44mm (1.73 inches)	0

Table 5.1National Institute of Justice Body Armor Standards

5.3 Comparison Graphs Against the Caliber Bullets

The separate graphs for ballistic impact resistance against aged and new standard samples by standard NATO caliber bullets 7.62 x 51 millimeter and 9 x 19 millimeter are already displayed in Chapter 4, i.e., modeling and Impact Simulations. Comparative graphs of stress induced onto samples due to ballistic impact are shown below [22]:

5.3.1 Aged Samples Stress Comparison against 9 mm Caliber Bullets

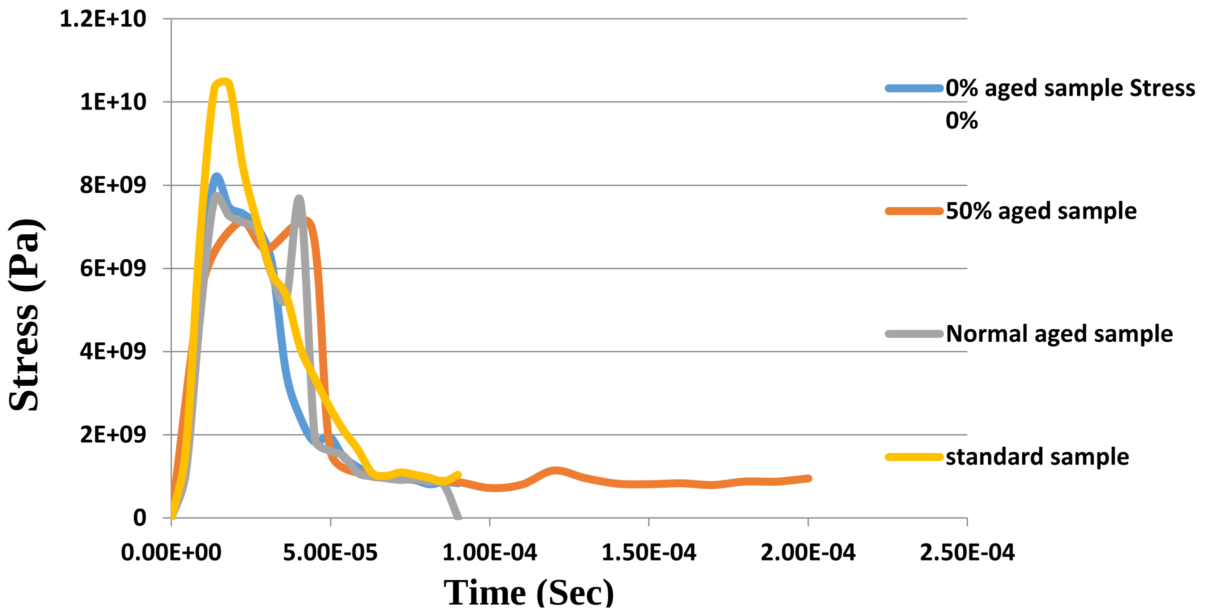

Figure 5.1 Aged Samples Stress Comparison against 9 mm Caliber Bullet

5.3.2 Aged Samples Stress Comparison against 7.62 mm Caliber Bullets

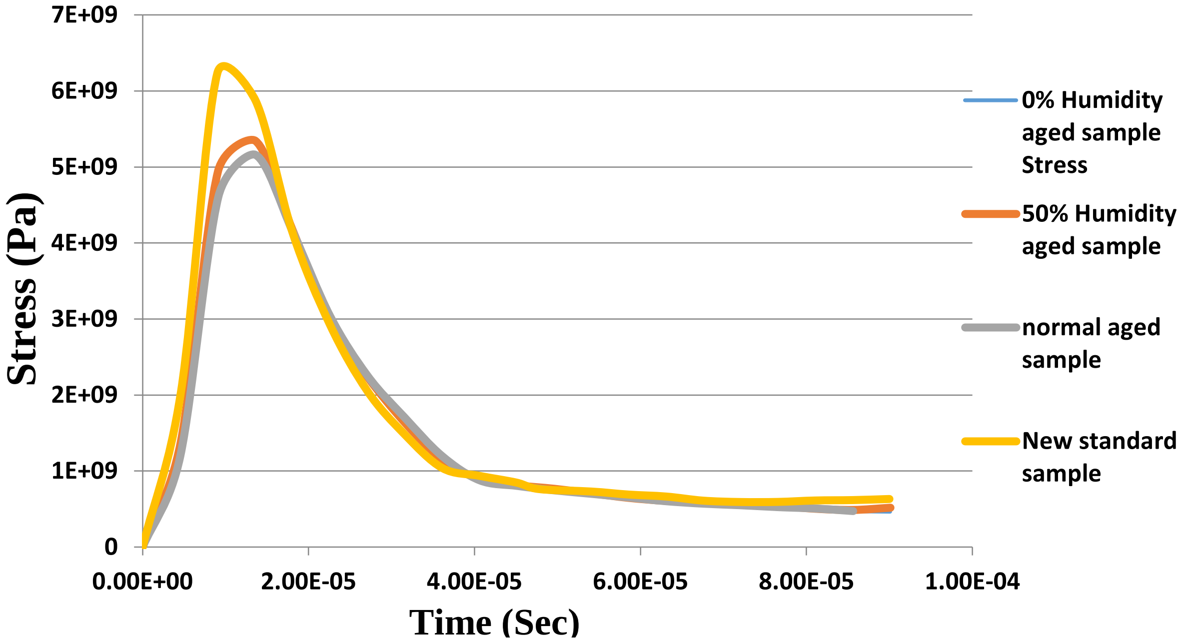

Figure 5.2 Aged Samples Stress Comparison against 7.62 mm Caliber Bullet

CHAPTER 6

CONCLUSIONS AND FUTURE RECOMENDATIONS

6.1 Conclusions

Ballistic proof body armors have been developed into a state of the art protective devices offering unparalleled protection from the life-taking physical threats that may be very much lethal. Still, the vulnerabilities in the use of ballistics safety materials, like bulletproof armor vests remain a basic and grave concern for the armies, the law enforcement agencies, and paramilitary institutes all over the world. Effective and guaranteed protection requires further research of soft body armor; that is, the identification and subsequent development of more efficient fiber, new meshing techniques, and other fundamentals that match future requirements of weapon effectiveness levels.

Advanced graphical models that may incorporate armor and the characteristics of a human body will be sought actively to establish novel technologies and products, and to avoid ballistic and fragmentary attacks while minimizing background signatures and blunt injuries sustained by armor. Regardless of the causes that contribute to old ageing, the time has a significant effect both on individual circumstances and on rapid ageing. The effect of temperature and humidity greatly decreases Dyneema ® UD SB21 mechanical and ballistic properties. During sustained exposure, the effect increased.

The simulations of the experimental data consequently resulted in a fact; it revealed that ageing plays a critical role to determine the life span of the product, i.e., Ballistics. Ballistic products undergo gradual degradation, like any other product, with the passage of time and usage. This process of degradation is aggravated with the application of mechanical load, temperature cycle treatment, and immersion of samples in liquid simulating human sweat. The results obtained from the samples showed similarity with this fact; when the effects of degradation in the artificial ageing composite were noted.

The NATO caliber bullets were used to apply the ballistic impact over the samples; and it showed some remarkable results. The caliber bullet used to induce the ballistic impact was 9 x 19 mm bullet and the results were noted to be quite conspicuous. Furthermore, the simulations also revealed that ageing has an adverse effect on the ballistic protective capability of vest; thereby it may compromise security and safety of its user. The aged bulletproof vest is more likely to impart greater trauma on the human body as compared to a new standard bulletproof vest.

6.2 Future Work Recommendations

The work done in this thesis is the basics of this field, which can lead to numerous advancements in the field that can prove to be much more beneficial and useful for mankind. Some of the possible work extensions that the further researchers can do are:

6.2.1 Simulation

The thesis is based on simulations and several simulations were done on ANSYS Workbench Explicit Dynamics (R1 2020) and the modeling was completed on SolidWorks (2018). Due to inherent limited availability of high tech computers and processors, fine meshing was not possible; therefore the coarse meshing was utilized. In order to further carry on this work, utilization of high tech computer or super-computer for swift computation of results is recommended. By adopting high end gadgetry one may be able to use ideal meshing and actual weaving pattern of fiber.

6.2.2 Experimental Analysis

This thesis utilized data already available for modeling and simulation against Dyneema product for ballistic impact resistance. Results of this simulations and modeling thesis can only be confirmed through actual testing of samples in ranges for ballistic impact behavior. It is recommended that actual data from ballistic impact testing ranges in Pakistan may be procured or utilized for simulation and further conformity. Moreover, accelerated ageing procedure may be done on the bulletproof vests available in Pakistan and then carry out simulation and actual ballistic impact testing. The effects of aged bulletproof vest on imparting trauma on the human body may be simulated by utilizing HSM/Human model of ANSYS.

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CERTIFICATE OF COMPLETENESS

It is hereby certified that the dissertation submitted by **Adnan Ahmad**, Reg. No. **171681**, Titled: ***Effects of Accelerated Ageing of Ballistic Composites on Impact Behavior*** has been checked/reviewed and its contents are complete in all respects.

Supervisor's Name: **Dr. Naveed A. Din**

Signature: ________________

Date: ________________