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*Review*

# Development of Natural Fibre-Reinforced Polymer Composites Ballistic Helmet Using Concurrent Engineering Approach: A Brief Review

**M. Z. Asyraf [1], M. J. Suriani [1,2,*], C. M. Ruzaidi [1,2], A. Khalina [3,4], R. A. Ilyas [5,6,*], M. R. M. Asyraf [7], A. Syamsir [8], Ashraf Azmi [9] and Abdullah Mohamed [10]**

1 Faculty of Ocean Engineering Technology and Informatics, Universiti Malaysia Terengganu, Kuala Nerus, Kuala Terengganu 21030, Malaysia; asyrafazman89@yahoo.com (M.Z.A.); ruzaidi@umt.edu.my (C.M.R.)
2 Marine Materials Research Group, Faculty of Ocean Engineering Technology and Informatics, Universiti Malaysia Terengganu, Kuala Nerus, Kuala Terengganu 21030, Malaysia
3 Department of Biological and Agriculture Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang 43400, Malaysia; khalina@upm.edu.my
4 Institute of Tropical Forestry and Forest Product (INTROP), Universiti Putra Malaysia, Serdang 43400, Malaysia
5 School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Johor Bahru 81310, Malaysia
6 Centre for Advanced Composite Materials (CACM), Universiti Teknologi Malaysia, Johor Bahru 81310, Malaysia
7 School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Johor Bahru 81310, Malaysia; asyrafriz96@gmail.com
8 Institute of Energy Infrastructure (IEI), Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, Kajang 43000, Malaysia; agusril@uniten.edu.my
9 School of Chemical Engineering, College of Engineering, Universiti Teknologi MARA, Shah Alam 40450, Malaysia; ashraf.azmi@uitm.edu.my
10 Research Centre, Future University in Egypt, New Cairo 11745, Egypt; mohamed.a@fue.edu.eg
* Correspondence: surianimatjusoh@umt.edu.my (M.J.S.); ahmadilyas@utm.my (R.A.I.)



**Citation:** Asyraf, M.Z.; Suriani, M.J.; Ruzaidi, C.M.; Khalina, A.; Ilyas, R.A.; Asyraf, M.R.M.; Syamsir, A.; Azmi, A.; Mohamed, A. Development of Natural Fibre-Reinforced Polymer Composites Ballistic Helmet Using Concurrent Engineering Approach: A Brief Review. *Sustainability* **2022**, *14*, 7092. https://doi.org/10.3390/su14127092

Academic Editor: Raul D.S.G. Campilho

Received: 13 March 2022
Accepted: 25 May 2022
Published: 9 June 2022



**Abstract:** In this decade, all researchers and industry players compete to develop sustainable product design by exploring natural fibre composites in product design development. One of the essential methodologies in creating composite products is concurrent engineering (CE). Industrial design and production engineering should be involved in the development of ballistic helmets. This publication aims to provide a quick overview of the evolution of natural fibre composite ballistic helmet designs. This manuscript is still in its early stages, but it already includes a summary of the progress of ballistic helmet design from 1915 to the present. Renewable materials, such as natural fibre, should be highlighted as an alternative to synthetic composites in developing a sustainable ballistic helmet design. Furthermore, launching the design development process for a ballistic helmet demands a CE strategy that includes multi-disciplinary knowledge. Computational modelling aids in the development of ballistic helmet designs, reducing the time and cost of manufacturing ballistic helmets. The ergonomic component of ballistic helmet design is also crucial, as is the thermal comfort factor, which can be handled using natural fibre composites with thermal solid insulating characteristics. The development of natural fibre composite ballistic helmets can be used as a consideration in the future as a revolution to create a sustainable design. Finally, this review can be used as a guide for industrial designers. In conclusion, this review might be utilized as a reference for industrial designers due to a shortage of studies, especially in producing product-related natural fibre.

**Keywords:** concurrent engineering; industrial design; natural fibre; product development; ballistic helmet

## 1. Introduction

Industrial design (ID) is critical in developing designs for products, equipment, items, transportation, furniture, and services that benefit consumers all over the world. However, most industry companies compete to offer attractive designs, new technology, and inexpensive and sustainable products. However, according to Isaksson et al. [1], industry firms still have difficulty integrating new product design or technology into the industrial design development process. As a result, the concurrent engineering (CE) method can build new product designs. According to Bertoni and Bertoni [2], this strategy is also commonly employed throughout product development procedures that demand a high level of safety and performance. This circumstance necessitates decisions from all design areas and must be determined early in the design concept phase. A lot of information and data are needed in the early design phases before establishing the scope required. The design process is not overly lengthy by excluding unneeded aspects. CE, according to Levandowski [3], has been found to reduce the probability of a design failing to fulfil standards.

CE is defined as a systematic approach to integrated design, related processes, including manufacture and support, according to the Institute for Defense Analyses (IDA) in the United States. As a result of this strategy, developers must evaluate all aspects of the product life cycle, including the product's concept, price, quality, scheduling, user requirements, and disposal. There are issues with traditional techniques for product design and manufacturing. CE is one of the ways that can help you produce a better product. In the design development process, barriers between design departments (designers) and manufacturing (engineers) must be broken down, and they must collaborate more [4].

Self-defence systems alone are worth 300 to 400 million euros per year on the global market, with an annual growth rate above 5% [5]. Ballistic helmets are a personal protective item commonly utilized by the military and law enforcement. This demonstrates the need for ballistic helmets to be redesigned such that they are more inexpensive, and the materials are widely available. Researchers have developed new composite materials incorporating natural fibres to reduce reliance on synthetic composite materials such as kevlar due to production costs, ease of supply, sustainability, and low weight [6–9]. According to Aji et al. [10], natural fibre has a number of advantages, including a smoother surface, renewable material, low density, cost-effective manufacture, harmless biodegradation, comparable mechanical qualities to inorganic fibre, recyclable in most countries, and the ability to modify the surface. Ballistic helmets are designed to protect the wearer's head while also being pleasant to wear, particularly during operations. According to Samil and David [11], the Personal System for Ground Troops (PASGT) has saved many lives of its users; however, there are still design and human factors flaws such as maintainability, balance, size, and weight. Furthermore, according to Davis et al. [12], combat helmets must also meet ergonomic standards and meet the requirements as protective gear. Materials and ergonomic considerations largely influence the development of ballistic helmet design. This research can inspire the design of a product, particularly personal protection equipment, in terms of the designer's role, who must collaborate with engineers to create a long-lasting and successful product.

## 2. Product Design and Concurrent Engineering

Product design is considered as a crucial stage to ensure the successfulness of a commercial product. A successful commercial product is commonly recognized as the item which can attain an acceptable amount of profit of a business company. Generally, product design can be described as mixtures of several components to establish a well-functioning product which is desired by the users [13]. The product design is required to link the industrial and mechanical design criteria to guarantee the product is well-accepted by the end users [14–16]. In this case, the progress of materials in product development goes hand in hand with the enhancement of manufacturing technology. Thus, to make sure a good optimization of product development, the product design process usually is being assisted by using concurrent engineering (CE) techniques.

CE is a well-established field which embedded the fundamentals of good product development processes. In product development, it is crucial to ensure the concurrent engineering techniques are well governed to produce a final product within a time frame that was agreed by all the stakeholders [17–19]. The stakeholders are involved in the aforementioned statement, such as constructors and suppliers in market supply chain. Generally, it can be appealed that CE is focused on milestones rather than the conventional focus on the product development process. The product development is defined as is a full-commitment process from a product development group to ensure a product right from a wide ranging design brief or customer requirement and details up to the manufacturing of a working prototype [20,21]. This process would translate the users' desires into physical items which combined the functionality around organization including engineering designers, manufacturing engineers, suppliers, technical support personnel, administrative and sale personnel [22–24]. A regular meeting will take place to have a good communication using advanced technology and information technology tools to have good communications among the organization members. Product development covers the product until it will be marketed and also other after sale issues such as recycling, warranty, disposal, and maintenance [25–27].

Many works have been established to embed various concurrent engineering models in the product development. The ground work of product design usually conducted by professionals which known as a designer such as design engineer, engineering designer or design and development engineer [28]. The engineering designers cannot isolate themselves from others, instead they need to work in collaboration with other teammates to cater all design problems in the early stage of the design process [29]. Generally, three main core activities are executed such as conceptual design, embodiment design and detail design in this product development, as displayed in Figure 1 [30]. Within these three core sub-activities, several contributing factors have to be installed in product design such as aesthetics, economics and investment climate, science and technology, sustainability and environment, market and industrial design in accordance to Johnson et al. [31]. Initially, the conceptual design is taking place as the initial stage of the product since the available resources is far lesser than that required during the manufacturing phase. In this case, the conceptual design phase is significant to make changes and still quite economical in comparison to the prototyping stage. Hence, the implementation of concurrent engineering in conceptual design would remarkably reduce costs by engaging other personnel early in the design process, whereby any changes done at this stage are very desirable. In conjunction to this process, computer-aided drawing (CAD) modelling and finite element analysis (FEA) were applied to aid the design process. Material selection is conducted simultaneously with achieving the design input actions to consider the material in the beginning stage of design process [32].

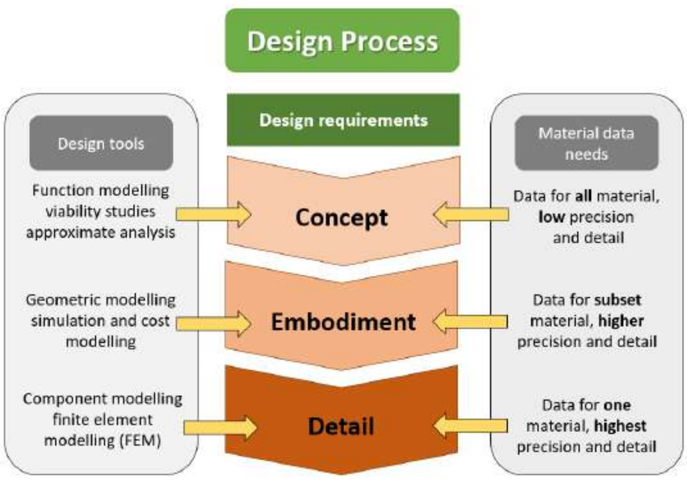


**Figure 1.** The design process in concurrent engineering which cover concept, embodiment and detail [13].

## 3. Ballistic Helmet from Design Perspective

The design and materials utilized in the construction of ballistic helmets have changed over time as new ballistic materials have been discovered and user problems have been addressed. Table 1 shows the evolution of ballistic helmets from World War I to present [33–36]. Besides that, there are lot of issue and problems experienced with an existing ballistic helmet as tabulated in Table 2. Since World War I (WWI), when the Hadfield helmet was derived from the Andrian helmet used by the United States Army, the design and materials utilized to produce ballistic helmets have evolved. The Hadfield helmet was then updated to the M1 ballistic helmet, which features an inner liner that can be adjusted to fit various head shapes [33]. During World War II (WWII), the Vietnam War, and even the Korean War, the M1 ballistic helmet became well-known. The M1 helmet, on the other hand, is still made of the same silver material as before [34]. The M1 helmet's design also includes flaws, such as overloading, insufficient thermal insulation properties, only one measurement, and incompatibility with portable communication equipment. The US Army began developing a replacement for the M1 helmet in the early 1960s [35]. Researchers have conducted ballistic helmet designs to build Personnel Armor System Ground Troops (PASGT). To replace the existing steel material in the construction of prior M1 helmets, the PASGT is made of Kevlar® fibre. Following the introduction of the PASGT by the US Army, two other combat helmets, the Advanced Combat Helmet (ACH) and the Lightweight Helmet, were created (LWH). A ballistic helmet design consists of three essential components, which are as follows:

**Table 1.** Evolution of ballistic helmets from World War I to present.

| Timeline | 1915 | 1943 | 1980 | 2005 | 2012 |
|---|---|---|---|---|---|
| Helmet Design | Brodie Helmet  | M1 Steel Pot  | PASGT  | ACH  | ECH  |
| Material | Rolled Steel | Fabric woven linear | Kevlar 29/PVB Phenolic | Kevlar 129/PVB Phenolic Twaron/ | UHMPE and Carbon Fibre |
| Helmet Threat(s) | Shrapnel | Fragmentation | Fragmentation 9 mm bullet | Fragmentation 9 mm bullet | Fragmentation 9 mm bullet and specified small arms |
| Areal Density | 2.2 psf | 2.2 psf | 2.2 psf | 2.2 psf | 2.0 psf |
| Tenacity | - | - | 23 g/d | 27 g/d | 37 g/d |

### 3.1. The Shell

The penetration test experiment determines the thickness of the helmet shell. The thickness of the helmet, according to Hamouda et al. [33], varies between 5 and 10 mm, depending on the function and the type of material employed. When the helmet is hit, the shell works as an energy absorber, allowing the energy to be transmitted to the foam. One of the most crucial aspects in the ability to absorb impact is the hardness of the helmet shell. Round-shaped helmets are typically designed to block as well as deflect direct blows on the helmet's surface. Salvaterra [37], on the other hand, discovered in a study that the softer helmet shell may survive focal strikes with high peak forces.

### 3.2. The Comfort Foam

When impact energy is applied to the helmet's surface, it passes through the comfort foam and into the energy management system. The head's impact energy is then reduced to a safe amount. When picking comfort foam material, consider the material's ability to absorb the helmet's shock energy [38]. Open cell foam varies from rigid linear foam in that it can absorb impacts greater than 10 $Kn/m^2$, which could cause pain in the head.

Energy cannot be withdrawn, but collision forces can convert it to heat and sound (acoustic waves). Each helmet design necessitates a different absorption force (high-velocity impact to low-velocity drop velocity).

### 3.3. The Retention System (Strap)

The human component is emphasized in every design. Figure 2 shows basic components of ballistic helmet design such as shell, retention system, and comfort foam. There is no exception in the development of ballistic helmet design. This is because human heads come in a variety of forms and sizes. A considerable number of helmet manufacturers, according to Hamouda et al. [33], produce helmets in four different sizes: 53–54, 55–56, 58–59, and 60–61 cm. Straps with a clip, Velcro straps, and straps with a ring are the three types of rental systems.

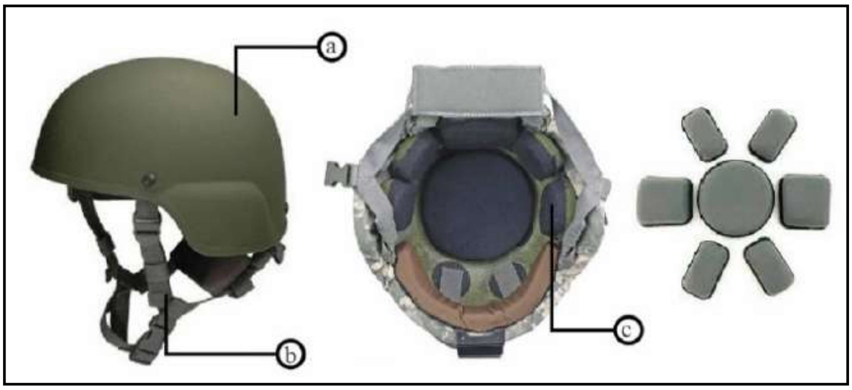


**Figure 2.** Basic components of ballistic helmet design: (**a**) Shell, (**b**) Retention System, (**c**) Comfort Foam.

**Table 2.** The issue and problems experienced with an existing ballistic helmet.

| Author (Year) | Issue and Problems |
|---|---|
| [11] | Ergonomic viewpoint such as heat retention, maintainability and weight |
| [39] | The development of ballistic helmet design should also take into account other factors that affect the efficiency and the human body such as thermal comfort and thermal insulation. |
| [39] | For now the study of thermal insulation of ballistic helmets has not been done. |
| [40] | A common problem reported among PASGT users is heavy and uncomfortable ballistic helmets. |
| [33] | Future models or prototypes of ballistic helmets will need to use a thinner material to reduce weight, have better ventilation and have better material strength. |
| [33] | Alternative materials are necessary to reduce reliance on the use of ballistic resistance materials that are not environmentally friendly and economical. |
| [41,42] | Stated to have investigated the possibility of using natural based fibre and fillers for armor materials. |
| [34] | In recent years, researchers have begun to be interested in developing natural fibres as reinforcement in polymer matrices for defense applications and ballistic resistant composites. |
| [35] | There are several factors that influence the performance of ballistic helmets such as ergonomic aspects, energy absorption mechanisms as well as material systems that need to be studied comparatively by analyzing technical reports and published research articles. |

## 4. Implementation of Natural Fibre Composites toward Sustainable Development

Natural fibre-composites or biocomposites are composite materials composed of reinforcement material distributed within a continuous phase (polymer matrix) [43]. The reinforcement material is made from natural fibres obtained from animal, mineral and plant by-products [44–47], as shown in Figure 3. For natural fibres, they can be extracted from the sources such as (1) plants including oil palm, sugar palm, kenaf, pineapple leaf, banana pseudo-stem, coir, rice husk, wood, and bamboo [48–50], or even from (2) animal by-products including shells, skins and feathers [51,52]. The reinforcement can exist in several shapes and sizes which include laminate, particles, and continuous or short fibres [53–55]. Generally, the natural fibres obtained from plant lignocellulosic fibre have three main constituents: cellulose, lignin, and hemicellulose, which influence its mechanical and physical performance [49,56]. The fibre usually exists in the form of a cellulose-reinforced lignin matrix along with a hemicellulose component as shown in Figure 4. Some of the advantages and disadvantages of natural fibres and synthetic fibres are explained in Table 3. The polymer matrix which is known as continuous phase was in form of thermosetting and thermoplastics polymers [57,58]. To produce products with natural fibre composite performance at optimum levels with the optimum natural fibre composite performance, it is essential to determine the properties of the composite, its chemical composition, synthesis and mechanical performance [59,60].

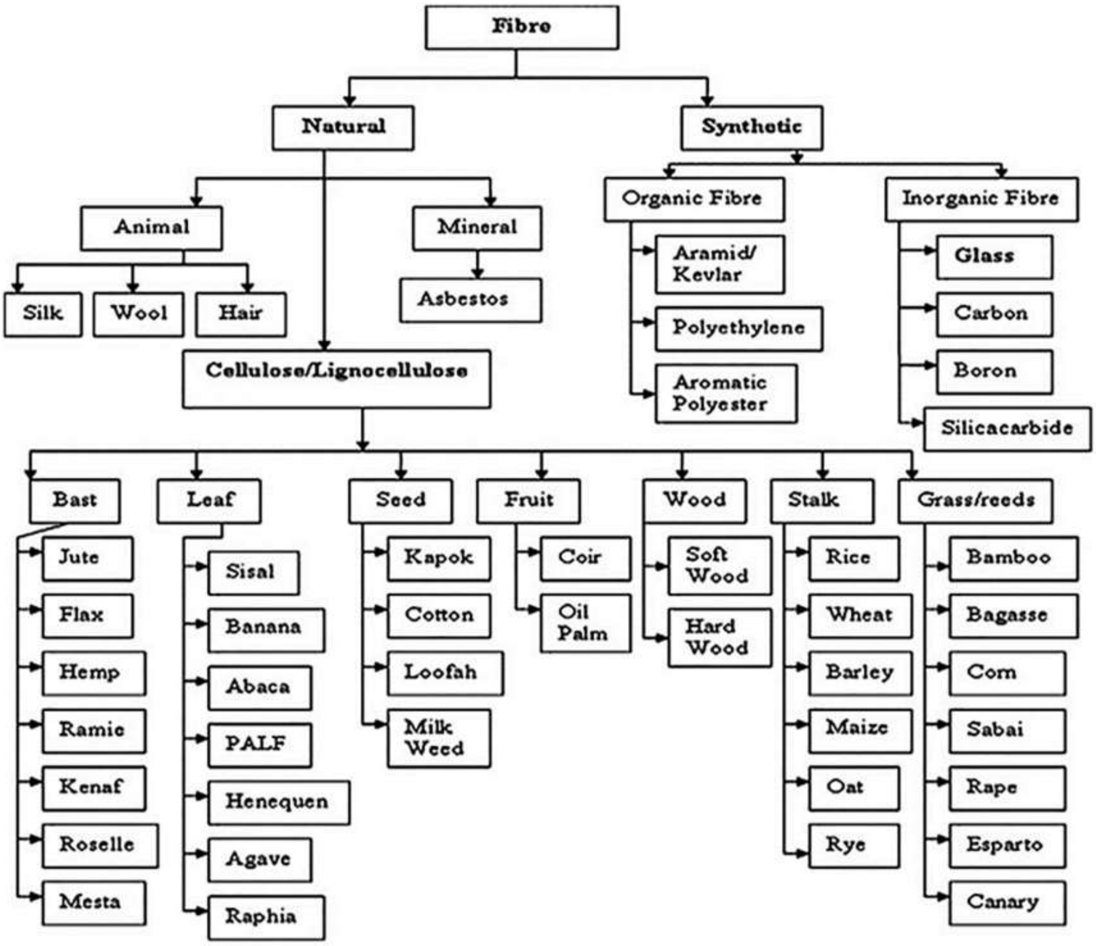


**Figure 3.** Schematic representations of natural fibres and synthetic fibres [60].

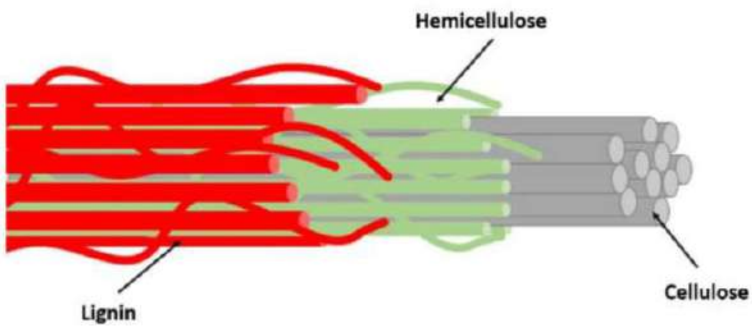


**Figure 4.** Schematic diagram of components of lignocellulosic fibre [60].

**Table 3.** Advantages and disadvantages of natural fibres and synthetic fibres.

| | Advantages | Disadvantages |
|---|---|---|
| Natural Fibre | Lightweight | Flammable |
| | Recyclable | Dimensional instability |
| | Improved specific mechanical properties | High moisture absorption |
| | Eco-friendly, carbon dioxide neutrality | Anisotropic behavior |
| | Do not generate any harmful gases during processing, low energy requirements during production | Limited processing temperature (~200–230 °C) |
| | Good thermal properties | Sensitive to UV |
| | Good acoustic properties | Fugal attack and microbial |
| | Low cost, availability, renewable resources, disposal by composting | Low strength than synthetic fibres, especially impact strength |
| | Non-abrasive and great formability | Variable quality, influenced by weather |
| | No dermal issue for their handling | Low durability |
| | Safer crash behaviour in tests | Poor fibre/matrix adhesion |
| Synthetic fibres | Long lasting | Flammable |
| | Readily pick-up to various dyes | Prone to heat damage |
| | Stretchable | Melt easily |
| | Waterproofing | Not eco-friendly |
| | Non biodegradability | Cause for microplastic pollution |
| | Moisture resistance | Not suitable for hot washing |
| | Strain and wear resistance | Poor insulation capacity |
| | High production | Moderate recyclability |

To develop an optimum natural fibre composite, a good selection of fibres, matrices natural fibre treatment, layering sequences and fabrication techniques could tally with the design intends. For instance, Ishak et al. [61] reported that sugar palm fibres have superior properties to resist the seawater and act as excellent water barrier properties. Later on, Misri et al. [62] had developed sugar palm fibre-reinforced polymer composite as a life boat due to its excellent mechanical and water resistant performances. This shows that selection of appropriate fibre with its matrix would exhibit significant functionality. Another important aspect in developing optimized biocomposites is to apply appropriate fibre arrangement and layering sequence. The fibres usually were arranged in many techniques such as multi-directional, randomly distribution of short or continuous fibres, bi-directional, unidirectional [63–65].

NFPCs are composites whose mechanical efficiency is determined by the interface of fibre-matrix adhesion with the stress transfer function, which transfers stress from the matrix to the fibre. Many researchers have reported on this in various studies [66–70]. Natural fibre characteristics such as volume fraction, physical qualities, impurities, moisture absorption and orientation play an important role in the determination of NFPC mechanical properties. Mechanical properties of PLA, epoxy, PP, and polyester matrices can be affected by many types of natural fibres and to show some of them. Figure 5 shows the Ashby plot of Young's modulus vs. tensile strength comparing the mechanical properties of natural fiber-based polymer composites with glass fiber–reinforced plastic (GFRP) and carbon fiber–reinforced plastic (CFRP), with carbon nanotube (CNT), and graphene–based polymer composites, and the mechanical properties of natural fiber-polymer composites, natural lignocellulosic fiber (NLF)/graphene-based composites, and NLF/graphene material [71]. The choice of matrix is extensive, covering a range of thermoplastics and thermosetting polymers. Recently, natural fibre-composites have been implement in wide spectrum of engineering usages such as aerospace [72,73], automotive [74,75], civil [54,76–78], safety appliances [9,79] marine [62,80], and medical [81–83] applications. It can be noted that the natural fibre composite has been widely used due to its excellent in mechanical performance and remarkable awareness among the public toward environmental sustainability [84,85]. Additionally, the upsurge of competition among industrial players in the global market for lightweight products has accelerated the application of natural fibre composites in many sectors [86,87].

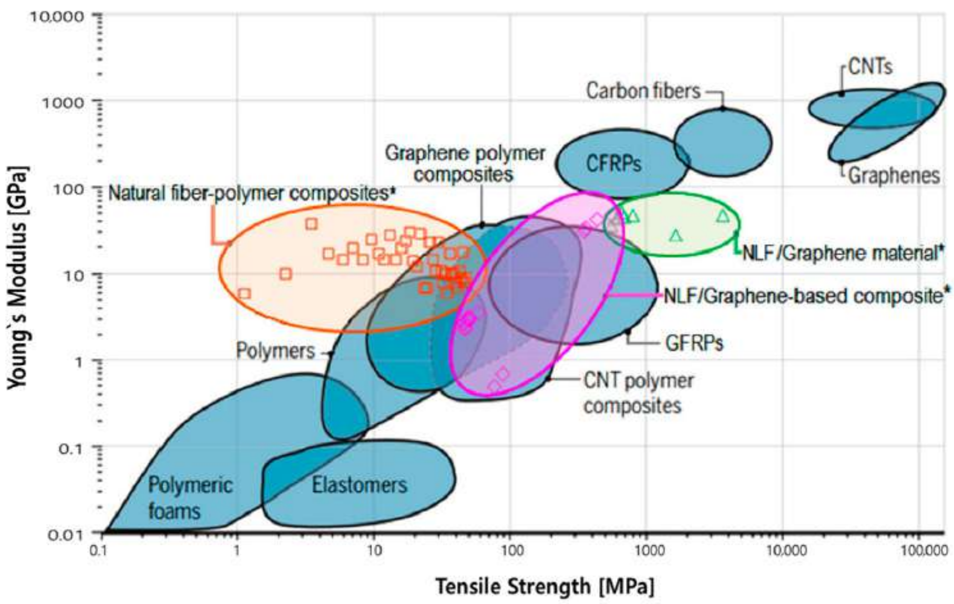


**Figure 5.** Some of mechanical properties of fibre-reinforced polymer composite.

## 5. Development Natural Fibre Hybrid Composite to Apply for Ballistic Helmet

The US Army initiated a design research programme to replace the M1 steel ballistic helmet design in the early 1960s. As a result of the programme, a single-walled ballistic helmet with improved protection and reduced weight has been developed. After that, more research was done on the resulting PASGT manufactured with Kevlar fibres. The US Army then continued its new ballistic helmet development programme, specifically the Modular Integrated Communications Helmet (MICH) and Advanced Combat Helmet, to reduce the weight of the PASGT ballistic helmet (ACH). ACH is a continuation of MICH's design evolution, and it is built of K129 Kevlar fibre, which has a density area of 185 versus 270 g/m$^2$ for K29 Kevlar fibre. Kevlar fibre K129 is 40% stronger than Kevlar fibre K29 (used for PASGT) [35]. According to Kadir Bilisik and Turhan [88], Kevlar K129 has a higher energy absorption rate than Kevlar K29.

There are two phases in the development of novel materials for ballistic helmets. Part one: chemistry, metallurgical science, and polymer science contribute to the invention of wholly new materials. The second section features a mix of new and classic materials and geometric and architectural elements [89]. Concerns about the usage of finite resources (synthetic fibre) and their environmental impact have encouraged researchers to look into alternative uses of natural fibres in composite hybrids [67,90,91]. A composite of two or more types of fibres will provide an advantage in overcoming the components' current weaknesses [92]. A study conducted by Wambua et al. [42], on the ballistic properties of jute, ramie, hemp, and hemp textile-reinforced polypropylene composites produced using hot compression molding, shows that the hybrid structures have a clear advantage over mild steel and the plain composites. Mild steel alone performs better than hemp and jute composites but slightly less than flax composites. In addition, it was found that the ballistic properties of the hemp composites increased significantly when a mild steel plate was used as facing and backing.

Studies on natural fibres on ballistic properties have been performed on jute, hemp and textile hemp-reinforced polypropylene composites produced using hot compression molding. According to a paper by Yahaya et al. [93] woven natural fibre composites offer outstanding mechanical behavioural qualities. The natural fibre has advantages: biodegradable, recyclable, better energy recovery, high strength and specific modulus, lower health risks, low density, low cost, less skin irritation, available in large quantities, low production costs, lightweight materials, less abrasion of equipment, reduced tool wear, improved energy recovery, and reduced skin irritation and respiration are all advantages of natural fibre development in developing countries [94–98].

## 6. CE for Natural Fibre-Composite Product Development

All aspects in natural fibre composite product developments such as customer needs, product design specification (PDS), concept generation, and detail design [97,99–101] have to be fully considered. Specifically for detail design, the elements such as component design and process design are essential for this stage [102–104]. According to Strong [105], component designs usually covered the sub-activities such as drawing or layout, constraints, analysis and material selection. For process design, the sub-activities under this element are, for example, manufacturing method selection, sequencing, machine/tool selection, system layout, integration of system and manufacturing procedures. In other research by Pugh [106], the CE is also covered in other processes of the total design including product design specification, market investigation and conceptual design besides being relevant in detail design. Even though there are two distinct types of philosophy in total design process, both Strong [105] and Pugh [106] entail simultaneous consideration of the manufacturing process at the product design stage. In this manner, the designers should embed design features in order to facilitate the fabrication process with lesser complexity especially when the manufacturing process is applied with hand lay-up technique [7,107,108]. For composites with fabricate using the hand lay-up process, the labour cost is a key cost element for lesser cost and to produce a large volume of product batch. Figure 6 depicts the main activities during the CE process which also recognized as the CE wheel that may lead to a 'wheel of fortune'.

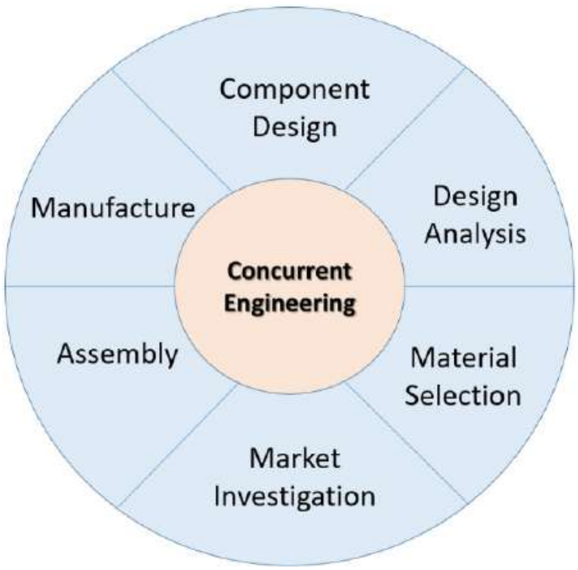


**Figure 6.** Concurrent engineering wheel [13].

## 7. Integration of Industrial Design and Engineering in Ballistic Helmet Development

CE is a critical component in composite product development. According to Sapuan [109], designing composite products necessitates a wide range of disciplinary knowledge. Seamless integration between product design and engineering is critical to building successful composite-based goods on the market. One of the sub-fields of industrial design is product design. According to the Pei [110], industrial design and engineering design have different design methods. The role of industrial designers is to develop the product's external look and develop the product employing ergonomics and aesthetics skill [111]. The engineer designer's job is to turn the concept created by the industry designer into a dependable, functional, and manufactured product [112]. This situation shows that the approaches to industrial and engineering design are distinct. This demonstrates that the development of high-quality, well-designed products is not only the responsibility of the product designer. According to Hassan and Hasri Yunardi [113], design integration is a form of design cooperation that stresses the integration of knowledge in the overall development of the design. According to Knoll et al. [114], CE is a method of approaching problems from multiple perspectives. CE provides several advantages, including (1) better and faster communication across departments and (2) fewer design revisions at the final stage before manufacturing.

The initial step in the production process is the design. Many significant decisions must be taken in the early stages of design that will impact the final product [87,115]. Concept generation is a technique for solving design challenges involving tools and concept development processes. Designers can use 3D image software to transfer ideas into diagrammatical, graphical, and modelling forms at the design concept level. The following are some composite concept generating methods:

1. Brainstorming;
2. Biomimicry/biomimetics (Analysis of Natural Systems);
3. Cross-industry innovation;
4. Analysis of existing technical systems;
5. Asking question method;
6. Gallery method;
7. Morphological chart method;
8. Blue ocean strategy;
9. Mind mapping; and
10. Theory of Inventive Problem Solving (TRIZ)

The CE approach needs to consider the entire product lifecycle starting from the beginning of the design process, manufacturing, cost, installation, sale, maintenance, disposal and process for recycling [116]. According to Sapuan and Nukman [116], 70% of the manufacturing cost of a product is determined in the early stages of design. This method is also widely applied in producing engineering product designs based on natural fibre composite materials. The CE approach is considered an integrated approach in design development. However, the design process, material selection and manufacturing process must involve experts in each field. Integration can be translated into computer systems such as Computer-aided design (CAD), Computer-aided manufacturing (CAM) and finite element analysis (FEA).

There are many factors that influence the redesign process of a product. These factors exist due to the problems encountered either because of the product itself or because of the consumer. According to Hassan and Hasri Yunardi [117], the main factors influencing the product redesign process are, for example, (1) materials (2) safety and (3) technology. In the development of ballistic helmet design, materials play an important role apart from the manufacturing process used as well as the ability of ballistic helmet design in protecting the user [33]. With the development of technology available today, it is possible to develop products that are more efficient in terms of weight, cost and energy. These advances have also led to the production of ballistic helmet designs that are lighter and more comfortable as well as able to increase the capabilities of ballistic helmets without burdening the user. According to National Academies Press [118], the ballistic helmet is one of the equipment of soldiers that requires the properties of mobility and agility. Figures 7 and 8 show the design process flow [119] and concurrent engineering process flow [120], respectively.

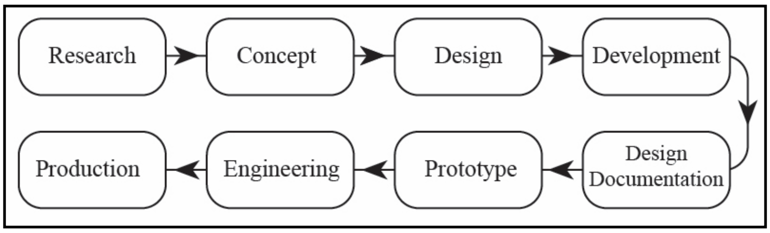


**Figure 7.** Design process flow.

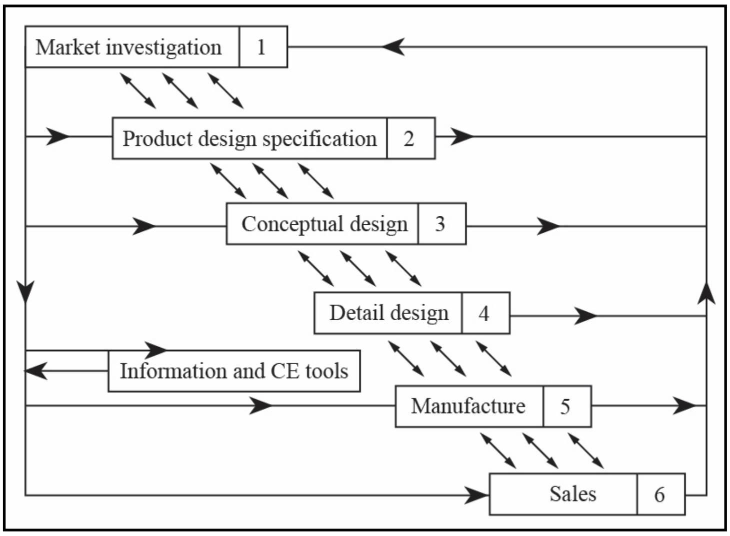


**Figure 8.** Concurrent engineering process flow.

## 8. The Role of Computational Modelling in the Development of Ballistic Helmet Design

Computer Integrated Manufacturing (CIM) is an automation system that employs machines and is controlled by a computer. Table 4 shows the elements of CIM system. The system is widely employed in the automobile, aviation, aerospace, and shipbuilding industries. CIM is a mix of two or more software technologies, such as Computer-Aided Manufacturing (CAM) and Computer-Aided Design (CAD) [121]. Production planning and scheduling, accountants, and shop floor forepersons who use the same database as product designers and engineers are all possible with the CIM approach, which is critical in developing a more advanced manufacturing field. The emergence of advanced manufacturing areas is at a crossroads [122]. This consolidation has some advantages, including a more organized development process and more accurate cost estimation.

**Table 4.** Elements of the CIM system.

| **Computer Integrated Manufacturing (CIM)** | |
|---|---|
| ➢ Automated work centres<br>➢ Manufacture<br>➢ Product design<br>➢ Marketing<br>➢ Purchase | ➢ Planning<br>➢ Information<br>➢ Finance<br>➢ Warehouse |

The development of ballistic helmet designs requires high costs in designing, making and physically testing prototypes to evaluate design performance [123]. Today, computational modelling is widely used in the development process to identify and make simulations on engineering-related problems. In addition to reducing costs, computational modelling methods can save time in developing a product design. This method's high efficiency and reliability can lead to its application to the development of composite hybrid ballistic helmet design [33].

The typical approach in ballistic helmet design development is focused on the experiment to evaluate the overall performance of ballistic helmet design. Prototypes made of various materials were necessary to develop ballistic helmet designs [33]. The prototype will be tested to determine its level of performance. If it fails to match the required standards, the design must be altered. The traditional strategy has shown to be effective. However, the traditional approach entails relatively high expenditures, numerous experiments, ballistic helmet design that does not reach ideal performance, a protracted development period, and the possibility of errors. As a result, computational modelling can be used as an alternate way to design, assess, and discover engineering problems at an early stage.

The contribution of computational modelling begins in the early stages of concept design. A designer develops some sketch ideas into three-dimensional (3D) drawings. The computational techniques such as modelling and forecasting of the microstructure of composite materials with natural fillers are essential in the development of natural fibre composite products. This was due to these tools acting as data-driven multi-physical modelling, leading to unexpected insights and exploration of the system properties [124]. The superior multi-functional behaviour of natural fibre composites lead to an extensive examination of their physical, mechanical and thermal properties under various exposure conditions [125]. Generally, this type of analysis is called as machine learning (ML) which functioned to analyse the behaviour of ballistic helmets under certain circumstances to be safely used for the user. The usage of ML in the designing stage of natural fibre composites is to link the findings of the large volume of relevant literature and highlight the broad spectrum potential of ML in applications such as prediction, optimization, feature identification, uncertainty quantification, reliability and sensitivity analysis [126]. Table 5 shows the computational applications and contributions in the development process.

**Table 5.** Computational applications and contributions in the development process.

| Computational Applications | Function |
|---|---|
| SOLIDWORKS, Autodesk AutoCAD, Autodesk 3ds Max | Designing and modelling |
| ABAQUS, LS-DYNA, NASTRAN, PRONTO 3D | Material mechanical Testing |
| AUTODYN-3D | Ballistic limit and damage |
| 3D Computational Fluid Dynamics | Thermal Comfort |
| DIGIMAT and Autodesk® Helius Composite | Simulation for new composite |

In detail, ML usually involved the CAD systems, which were applied in the simultaneous work on the 3D solid model and the 2D drawing using two separate files, with the drawing looking at the data in the model; when the model changes, the drawing will accordingly update [127]. As 3D solid models change, 2D drawings are also updated. To produce a solid 3D model, the designer can apply software SOLIDWORK, Autodesk AutoCAD, and Autodesk 3ds Max [21]. Computational methods are also becoming a popular trend in testing composite materials. Therefore, numerical simulation is one of the alternative methods that can be used to analyse the impact behaviour of ballistic helmet design materials in a more economical way than traditional approaches. Computational simulations such as ABAQUS, LS-DYNA, and NASTRAN, PRONTO 3D are used to test the mechanical properties of composite materials. Numerical simulations are also used to identify the damage of composite materials during ballistic impact, not requiring experimental testing. AUTODYN was used to identify damage characteristics and ballistic limits as in the Kevlar 29/Vynilester panels study [33].

## 9. Ergonomic Aspects of Ballistic Helmet

It is critical to build a product or service that can provide humans with the most convenience. Ergonomic is derived from the Greek terms 'ergo' (work) and 'nomos' (work norms). According to Muhammad Fauzi [128], the International Ergonomics Association (IEA) defines ergonomics as a science that analyses the interaction between humans and all aspects of their environment using theoretical concepts, principles, data, and methodologies. Furthermore, ergonomics studies human physiology and psychological characteristics to optimize the human–machine–environment system.

Cognitive, application, and industry ergonomics are the three types of ergonomics as shown in Figure 9. One example of ergonomic uses is ballistic helmets. Various elements must be considered during the development of a ballistic helmet design. The first consideration is the ability to withstand a gunshot without penetrating the helmet shell. The human element is the second factor, which refers to how the helmet's design affects the wearer, and includes fit, comfort, maintainability, and weight [40]. The Malaysian army studied the ergonomic characteristics of the PASGT ballistic helmet at Camp Wardieburn. According to Samil and David [11], users of ballistic helmets experience issues such as heat retention, high weight, and maintainability. The increased load caused by ballistic helmets makes the wearer feel uneasy.

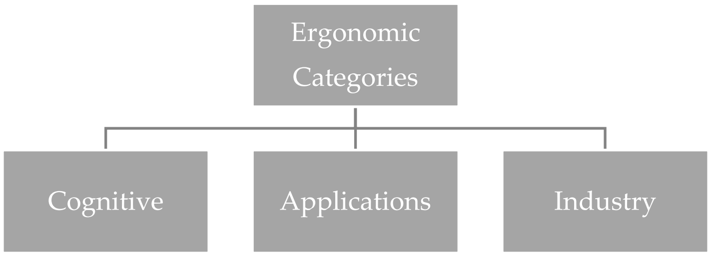


**Figure 9.** Ergonomic Categories.

Ergonomics is a multi-disciplinary field with practitioners from a variety of backgrounds. Ergonomics' multi-disciplinary character is a strength of the field [12]. However, because ergonomics are interdependent, a variety of issues develop [129]. According to Davis et al. [12], there are no guidelines or frameworks for systematically collecting and analysing ergonomic data on ballistic helmet designs that give consistent or validated data. Ballistic helmets are made up of three main components that operate together [130]. If one of these components fails to function correctly, the ballistic helmet's capabilities, comfort, and operational performance will be harmed; this demonstrates that the ballistic helmet components have a 'functional relationship'. After two rounds of Delphi surveys, fit, ease of use, stability, physical comfort, mass, the centre of mass (COM), thermal comfort, visual awareness, mass moments of inertia (MMOI), audible awareness, speech intelligibility, equipment compatibility/integration, operational performance, and user acceptance were identified as the fourteen ergonomic attributes of ballistic helmets.

Thermal comfort is when the mind expresses satisfaction with the thermal environment, and this assessment is subjective [131]. Figure 10 shows the Thermal Comfort Influencing Factor and Effects Ballistic Helmet [12]. The human body can be compared to a heat engine, in which food is the input and surplus heat is released into the environment so that the body can continue to function. According to the Chartered Institute of Building Service Engineers, the average human produces 115 W of energy each day. It is a metabolic by-product of the food that has been consumed. According to Zingano [132], the normal human temperature index is divided into three parts, namely 36.6 °C (oral), 35.8 °C (skin), 37 °C (anal) and 37 °C (internal organs), while the skin temperature becomes temperature benchmarks to achieve human thermal comfort. The three most prevalent body index temperatures, according to Zingano, are 36.6 °C (oral), 37 °C (anal), and 35 °C (skin temperature).

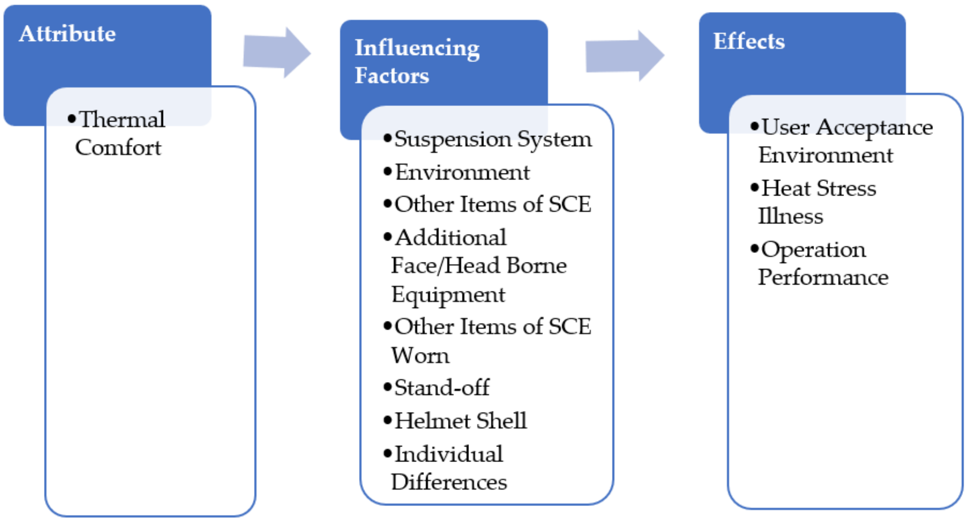


**Figure 10.** Thermal Comfort Influencing Factor and Effects Ballistic Helmet.

The human head makes up 9% of the human limbs and plays a significant role in the thermoregulatory process and preserving the limbs' thermal comfort [39]. Meanwhile, Bogerd [133] discovered that the head is responsible for the majority of heat loss. The research by Mohamad Asyraf Azman et al. [134] also states, the human head is a significant component of the human cooling system. Its goal is to keep the user's body heat in check. The closed region of the head will rise above the normal body temperature if it is closed [39]. This finding demonstrates that the head cover's thermal insulation value has a direct impact on the amount of heat produced. The six factors affecting thermal comfort are listed in Table 6 [135]. This knowledge is critical in defining how materials should be used in the construction of ballistic helmets. The composite material properties to be employed, such as fibre type, matrix, fibre composition in the matrix, fibre interaction with the matrix, and composite manufacturing process parameters, should all be investigated during the redevelopment of the ballistic helmet design. Designers and engineers must guarantee that the end product of the design can provide optimal comfort to the wearer even in a high-risk situation while redesigning ballistic helmets.

**Table 6.** The six factors affecting thermal comfort.

| Main Factors | Basic Factors |
|---|---|
| Personal factors | Clothing insulation |
| | Metabolic heat |
| Environmental factors | Air temperature |
| | Radiant temperature |
| | Air velocity |
| | Humidity |

## 10. Conclusions

The article is expected to deliver a comprehensive review on the implementation of concurrent engineering (CE) on development of natural fibre-composite ballistic helmet in military application. The natural fibres are obtained from three different sources such as plant wastes, animal by-products and mineral resources. The plant lignocellulosic fibres were highly demanded among emerging materials since they use less energy consumption and are non-toxic to nature and humans. It is well-known that natural fibre-composites have excellent physico-mechanical performance due to the cellulose component providing good shape and structural integrity for the fibres. Most common natural fibres used in composite products are flax, coir, hemp and jute, meanwhile, roselle, sugar palm and kenaf as those emerging fibres. However, there are three natural fibres that have high potential in the development of ballistic helmets, namely kenaf, bamboo and sugar palm. This phenomenon led the natural fibres to become suitable to be integrated with polymer in composites. This can benefit various industries especially ballistic application since the material exhibits a low density, less solidity, and cheap price compared to other conventional materials. Thus, good combinations of natural fibre composites along with CE in ballistic helmet development would enhance the properties of the products and their materials toward optimized strength as well as their functionality. These techniques would define appropriate problems of users and refine them in terms of the products funtionability. Industrial design and manufacturing engineering need to develop together in the development process of ballistic helmets by applying the CE approach. The CE approach has many advantages, such as identifying problems at an early stage and minimizing design defects. It simplifies the engineer's role to interpret the conceptual design into a functional and reliable product. In addition, this review can also help industrial designers better understand the role of creating natural fibre composite products, especially for developing ballistic helmet designs. Lastly, an appropriate manufacturing process is tallied with the product design of ballistic helmets and their applications.

**Author Contributions:** Conceptualization, M.Z.A. and M.J.S.; investigation, M.Z.A. and M.J.S.; writing—original draft preparation, M.Z.A. and M.J.S.; writing—review and editing, C.M.R., A.K., R.A.I., M.R.M.A., A.S., A.A. and A.M.; supervision, M.J.S.; project administration, M.J.S.; funding acquisition, A.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by FRGS/1/2020/TK0/UMT/02/4/Correlation of Manufacturing Defects, Interfacial Adhesion, Physical and Mechanical Properties of Plant Fibre Reinforced Hybrid Composite Material Towards Compatibility Behaviors/Vot No 59624.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Acknowledgments:** Authors would like to thanks all the staffs of Maritime Technology Laboratory, Biocomposite Lab, INTROP, Advanced Engineering Materials and Composites Research Centre, UPM and MSET Inflatable Composite Sdn. Bhd. for their great helps.

**Conflicts of Interest:** The authors declare no conflict of interest.

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