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TOPICAL REVIEW

Armours for soft bodies: how far can bioinspiration take us?

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1. Introduction

and stiffness equate to encumberment which must be balanced with the potential for the defensive structure to absorb impact energy. For example, smaller, faster animals have developed less armour-like protection as they derive greater survival rates with their ability to evade without these structures to weigh them down. With ballistic armours, the relative velocity of the user to the threat is quite low and therefore, the analogues examined below come from larger or slower animals that have had to develop physical methods of protection as their primary form of defence. This review will focus on three types of natural armour: mammalian dermal shields as an analogue to soft armour, turtle shells and arthropod exoskeletons for hard armour, and scales which combine flexibility and protection in a way that has yet to be successfully mimicked in a modern man-made armour systems. The selection of natural analogues was completed by comparing methods for energy dissipation in form factors that allowed sufficient mobility for the hosts. For example, the shellfish were not considered because the protective shells do not integrate with a means of locomotion. The intent is to find the convergence between biological systems and engineered armours to be able to enhance survivability in future conflict.

2. Background: ballistic armour

As has historically been the case, the higher the threat level, the greater the weight and bulk necessary in the armour to defeat it. Due to the ever-expanding range of threats, many countries and organizations have developed standards to benchmark protection levels. In the United States, the National Institute of Justice (NIJ) maintains the most commonly used standard for ballistic resistance of body armour, 0101. The most recent version of the NIJ standard, 0101.06, comprises five different protection levels evaluated against the threats laid out in table 1:

Types IIA through IIIA comprise the handgun protection levels while levels III and IV are rifle rated armours as shown by the increased test velocities. Each successive level represents a greater impact energy (either through increasing projectile mass, velocity, or both) that the armour system must mitigate to successfully defeat the threat. Successful defeat is usually defined by two metrics: backface deformation and resistance to penetration (RTP). RTP can quite simply be defined as the ability of the armour to stop the incoming projectile before rear surface of the armour is penetrated and the projectile contacts the wearer. Backface signature or deformation (BFS or BFD) is a measure of the impact force applied to the user during the successful defeat of the projectile. Behind armour trauma can be as fatal as the projectile itself so most standards specify a maximum allowable deformation measured in clay or ballistic gel during testing. For example, to successfully pass the NIJ standard at any level, the armour must not only stop the specified threat from penetrating at the specified velocity, but also must have a maximum BFS depth of 44 mm or less [13]. The clay used in this test protocol captures the transient deformation of the armour and therefore the maximum deflection at any point during the ballistic event can be measured. Therefore, increasing impact energies require increasingly sturdy armour designs to be successful. Modern soft armour is capable of attaining up to the IIIA level of protection. To stop the rifle threats, Levels III and IV armours currently require hard armour designs.

Defeating a ballistic threat can most simply be described through an energy balance. The input of energy into the system by the threat must be absorbed or dissipated in the armour and/or the wearer in full. Therefore, in a successful RTP test, the equation can be written simply as follows:

$$E_0 = E_A + e_T A \tag{1}$$

where E_0 is the energy of the penetrating threat (kinetic energy in the case of ballistic protection), E_A is the energy absorbed by the armor system, and e_T is the energy per unit area transmitted to the wearer multiplied by A, the area the impact is dissipated over. Measurement of the BFS is intended to estimate the e_T as a way to quantify the likely behind armor trauma. In some cases, measurement of the volume of the penetration into the witness clay has been used as a more accurate measure of energy imparted to the body [14] but this is not yet an industry standard. Energy can be dissipated by the armour through absorption via elastic and in-elastic deformation, or through distribution by de-localizing the impact energy. Both methods may result in a deformation of the same volume, however, direct absorption without distribution will result in a much higher BFS measurement. This high e_T due to the localized impacting energy can have a much more damaging effect on the wearer through behind-armor blunt trauma (BABT). Therefore, a common theme in the armor discussion to follow will be how the energy is transmitted to the user as this plays a large role in the survivability of the event.

however, given the similarities to the skin of other mammals (including humans), there is a plethora of available works that could be applied. Many early studies looked to linearize the stress–strain relationship of skin in numerical models which fails to accurately capture the J-shape of the curve due to collagen fibre orientation. While this may be sufficient for highly dense, oriented samples like rhinoceros' dermis, it fails to capture the full complexities of the mechanical behaviour. Some of the earliest work to develop constitutive equations for mammalian skin was performed by Lanir and Fung based on experimental data in observations of rabbit abdominal skin [33, 34]. These relationships, however, were dependent on preconditioning of the skin sample and required different equations for loading and unloading. Ridge and Wright looked to develop a relationship between the orientation and involvement of collagen fibres in a tension test with the mechanical performance of the dermis [30]. The relationships developed by Tong and Fung in [35] defined a 'pseudo strain potential' for the skin samples to begin to derive the stresses acting on the material in three dimensions. Sherman *e a* benzobis-oxazole (PBO) such as Zylon® (Toyobo) [41]. Many works have also looked at spider silk as a biological replacement for engineered ballistic fibres due to their strength-to-weight ratio and elongation at failure [42–45]. During a projectile impact, the projectile is caught in the fibres and the kinetic energy is absorbed through fibre interactions and failure. Breaking down the simple energy balance from equation (1), E_A can be further described through

$$E_A = E_{TF} + E_{ED}. \tag{4}$$

Where E_{TF} is the energy absorbed in tensile failure of the yarn and E_{ED} is the energy absorbed in elastic deformation [46]. This process is shown graphically in figure 4.

The elastic deformation term can be thought of as a combination of the elastic deformation of the yarns and fibres along with the deformation of the fabric. The fabric deformation includes frictional absorption mechanisms like inter-yarn friction, fabric projectile friction, and interactions between fabric layers [39, 48]. It has been shown that the inter-yarn friction plays a critical role in energy dissipated in frictional work at the yarn-to-yarn junctions [49–51]. This affects the stiffness of the yarn in the tensile direction and the fabric in the transverse direction which, in turn, affects the performance of the material [52]. The inter-yarn friction can be described by the static frictional coefficient between the yarns while yarn-projectile friction can be better described by the coefficient of kinetic friction [53]. This highlights the importance of the weave or fabric structure in the energy absorption of the overall system. Manufacturers also may stitch soft armour packages in the transverse direction to enhance these frictional forces while maintaining flexibility. The weave of the fabric provides the similar interactions as the lateral crosslinking in mammalian dermis while the quilt-stitching replicates at least a portion of the transverse linkages. In fact, quilt-stitching was shown to increase the energy absorption in fragment impacts 14%–22% over non-quilted armours [54].

The other major energy absorption mechanism is through tensile failure of the yarns. Some ballistic fabrics, such as para-aramids, have been shown to exhibit strong strain-rate dependencies [55, 56]. It was found that the strain at failure decreased with increasing strain rate in Twaron® fabrics. This limits the energy that can be absorbed in fibre elongation and causes fibre failure in the brittle mode [39]. However, UHMWPE fibres have not be shown to demonstrate a strain-rate dependency which may lead to increased energy absorption [57]. While fibre elongation is an important mechanism for absorbing energy, it needs to be balanced in ballistic testing to limit back deflection [14]. As discussed above, this back deflection transmits energy into the body of the wearer causing BABT which can be potentially life-threatening. Like dermal armours, the soft nature of fabric armour localizes the damage creating sharp BFS deformations. Localized damage means that the remainder of the armour is likely undamaged and can withstand multiple impacts, but the total energy absorbed byand mnot t me-3 (i e)fored146 T -

ing blow and the inner structure provides the bulk of the energy absorption through deformation.

Another point of interest on arthropod exoskeletons is how they provide protection without restricting motion. Looking at the exoskeleton as a system of defence rather than just a defensive structure can provide ideas of how to offer the most amount of protection without sacrificing freedom of movement. Unforion witho4-30 (p)3 (r)14 (op(ot)9 (e)-2.1 (c)-4.)-2.1 witho4-30 (p)3 (r)14 pn uceasue it (r)14telaeeaTw T[(t)9 (e)-3
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functionally graded material structure of the carapace to blunt a predator's attack and distribute the energy input to their soft tissue [91, 98].

The hierarchical structure of a turtle carapace is designed to provide protection from impacts. With a highly dense exterior component to mitigate impact and a softer supporting structure for shock absorption, the carapace can withstand relatively large applied loads. While a carapace would be unlikely to perform well in a ballistic event, the design of the structure and mechanisms for energy absorption echo the intent of man-made armours. The interior foam-like structure absorbs and dissipates the impact energy as a ballistic protective armour should to mitigate BFS. As will be discussed in the hard armour section below, the highly dense and rigid exterior plays an important role in blunting the initial contact of the incoming threat. Also, similar to hard armour protection, the carapace is bulky, heavy and cumbersome. Again, a much higher level of energy absorption can be obtained but the cost is rigidity. As mentioned, different species balance the trade-offs to be more effective in their environments. In some cases, speed and agility may be preferred for hunting and evasion rather than maximizing protection. But for slow moving terrestrial turtles, being able to fully retract into their shells if necessary, mobility is less of a concern. As an analogue for the modern soldier, mobility is not optional and the ability to escape and evade is critical to survival on the battlefield.

4.3. Man-made hard armour

As mentioned above, hard armour is utilized today when it is necessary to defeat rifle threats (NIJ Level III and above). Depending on the intended threat class, designers may employ plates made from solely polymer matrix composites or may use hard ceramic cores. Semi-rigid armour plates and combat helmets are made from fibre reinforced polymer matrix composites based on fibres like those used in soft armour. The difference here is the addition of a resin matrix to bond layers together in the transverse direction. The resin matrix constrains the yarns of the fabric so that the projectile must engage and fracture more fibres directly to penetrate the material. Additionally, the resin enhances the frictional forces between yarns and plies so the composite has more energy absorption potential than similar soft armours [51, 99, 100]. The stiffer the resin used, the greater the yarn confinement and generally the greater the absorption potential of the laminate. However, fibres must still be able to move

macroscopic model for the pulverized ceramic ahead of the projectile to obtain a detailed picture of the penetration process [109]. Bürger *e a* developed an FEA model of an armour-piercing projectile impact on a ceramic/composite armour with special attention paid to the delamination between the backer and strike-face during the defeat [110]. Due to the multitude of deformation processes occurring during impact, including large strains and fracture, the most effective modelling techniques rely on mesh-free FE analyses. One method, smooth particle hydrodynamics, borrowed from fluid dynamics appears to show the most promise in predicting ballistic results. An overview of the method and it's applications is presented in [111]. Lee and Yoo found good correlation between ballistic experiments and armour tiles designed with metal backing plates using this method [112]. In total, these models present a detailed depiction of the defeat process in hard armour but so far have not been accurate enough to replace physical ballistic experiments.

While a hard armour plate provides substantially higher protection from ballistic threats, the stiffness, thickness, and weight takes a toll on the user. As described in the defeat mechanisms, this type of architecture must be rigid and therefore mobility will be inherently reduced. Soldiers use a set of plates in an attempt to cover all the vital organs in the torso but there are gaps in coverage to maintain mobility. The thickness of commercially available armour exacerbates this issue. Military level torso plates are usually about an inch thick; lower performing systems may be thinner. These factors combined with the system weight has been shown to have a severely negative effect on users. One study showed that a standard by scale shape, size and overlapping distance. While scale size will vary considerably between species of fish, normalized overlap distance has been shown to be remarkably consistent [119]. In the following sections, an overview of the current research into scale interactions and modelling approaches will be reviewed along with the applicability for future armour development.

As mentioned above, the asymmetrical composition of fish-skin gives rise to its unique mechanical properties. These properties are characterized by a highly anisotropic response in bending due to the scale to scale interactions. Vernerey and Barthelat demonstrated this with a simple pinch test of fish-skin. Bending in the direction of the scales (scales on the inside) showed significant scale rotation and increasing bending resistance while convex bending showed no stiffening [119]. The stiffening response can be described via a simple 1D model relating stiffness to radius of curvature. Figure 9, below, introduces the setup for this model:

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ever was shown to depend on localized scale bending [124]. Furthermore, these responses can be tailored by changing scale size, overlap distance, and scale stiffness [125]. Therefore, a fish may have evolved with a scale structure such that the scales lock against each other before soft tissue damage occurs. Similarly, a ballistic structure could be designed to lock before a small ballistic penetrator can reach a certain depth.

Another factor that makes scales highly desirable in a defensive structure is the ability to distribute the force of penetration or impact loads over a larger surface area and limit e_T. The scale overlap allows for when the scales can interact, the force can be distributed [126]. Browning *e a* demonstrated that the back deflection of the scaled surface was dependent on the density of the scale arrangement and therefore could be tailored to mitigate blunt trauma [127]. However, in this case, the structure bending response was dominated by scale bending as the sample design limited scale sliding resulting in a nearly linear stress–strain response. Figures 10 and 11 illustrate how scales can distribute the loading of an impact to mitigate trauma. While the load is distributed over a larger surface area, damage to the structure is still relatively localized to the armour because cracks cannot propagate between adjacent scales. Therefore, unlike monolithic structures, each impact on a scaled structure would behave like an undamaged panel as long as impacts were not on directly adjacent scales. Fish-skin presents a defensive structure unlike those currently available for ballistic protection because it aims to balance of mobility and protection. The imbricated structure allows for the benefits of both types of armour to be incorporated into a single system. Currently, there is no well-accepted in-between for man-made ballistic armours; simply hard or soft packages. In natural defensive structures, scales utilize the best parts of the hard and soft protective systems to create protection that supports motion [128]. The additional energy absorption mechanisms and ability to distribute loading are large factors in the appeal of scales for future armour systems.

5.1. Man-made compound armours

While there is no well-accepted armour on the market that takes advantage of the structural advantages of scales, some companies have tried. The most well-known system to try this was Dragon Skin developed by Pinnacle Armor. Dragon Skin utilized overlapping ceramic discs to create a ‘scaled’ strikeface backed by neat Kevlar® fibres, shown in figure 12 [129]. This was the subject of intense controversy between the US Army and Pinnacle Armor due to their ballistic claims following its release in the early 2000s. A consequence of this is that there is a lack of reliable information as to its true ballistic performance. What is known however, is that the modular strikeface offered an improvement in multi-hit performance due to the restriction of ceramic fracture propagation to individual tiles but the cost of this performance was increased system weight. One belief is that each scale needed to be thicker than the ceramic component of a monolithic plate of the same performance because the scale geometry did not allow for proper support of the ceramic which limited the dwell time and thus the ballistic effectiveness. This coupled with scale overlap is commonly blamed for the increase in weight. Additionally, there was not a substantial increase in flexibility due to the bulk of the system. However, this remains an area of interest because of the severe effect body armour can have on a soldier’s effectiveness. While Dragon Skin used a ‘scaled’ strikeface, it did not truly replicate the interactions of scales in nature. For example, this bio-inspired structure lacks an analogue to the dermal pocket which controls scale rotation. Ceramic scales would have no ability to bend before breaking so this mechanism cannot be used to enhance energy absorption. Therefore, to gain a benefit from the scaled structure, scale sliding and rotation must activate. Without a dermal pocket analogue, these factors also may not be in play. With a greater understanding of how this protection is accomplished in nature, it may be possible to realize an armour system that can outperform the current standards without an added weight.

5.2. Future of compound armour systems

As discussed, there are several ways to build armour for personal protection but each method requires trade-offs for the user. Because of the weight and mobility constraints, coverage is often limited to vital areas. For example, the US military utilizes soft armour vests to cover the majority of the torso with a set of four hard armour plates to cover critical organs on the chest, back, and sides. While it has been noted that vests change the distribution of injuries to unprotected areas [130–132], there are still gaps in coverage on the torso that would be vulnerable to high-powered rifles. Similarly, there is often little to no protection on the lower body due to the deleterious effect it would have on mobility. One study of firearm trauma over a three-year period in Israel noted 53% of e(iounsem)-2 (e-)]rs(o)3 (

References

[1] Meyers M A, Chen P-Y, Lin A Y-M and Seki Y 2008 Biological materials: structure and mechanical properties *P, . Ma e . Sc* . **53** 1–206

[2] Vincent J F V, Bogatyreva O A, Bogatyrev N R, Bowyer A and Pahl A-K 2006 Biomimetics: its practice and theory *J. R. S c. I e ace* **3** 471–82

[3] Gill J 2016 Medieval Europe and its relation to contemporary weapons development *BA T. e .* University of Puget Sound (https://soundideas.pugetsound.edu/history_theses/21)

[4] Ehrlich H 2017 Materials design principles of fish scales and armor *B, , ca Ma e a., Ma e O* (Dordrecht: Springer) pp 237–62

[5] Arciszewski T and Cornell J 2006 Bio-inspiration: learning creative design principia *I e e G, t, E ee a d A c. ec t e* (Berlin: Springer) pp 32–53

[6] Nickel H, Pyhrr S W and Tarassuk L 1982 The art of chivalry: european arms and armor from the metropolitan museum of art : an exhibition *Me , , . Mt . . A* 181

[7] Miller D J 2011 Design and analysis of an innovative semi-flexible hybrid personal-body armor system *T. e .* University of South Florida (http://scholarcommons.usf.edu/etd/3247)

[8] Agrawal B J 2011 High performance textiles for ballistic protection *2011 De e . e Sc e ce Re ea c. G e e ce a d E, (DSR)* pp 1–4

[9] Vernerey F, Liu W K and Moran B 2007 Multi-scale micromorphic theory for hierarchical materials *J. Mec. . P. . . S d* **55** 2603–51

[10] Fratzl P and Weinkamer R 2007 Nature's hierarchical materials *P, . Ma e . Sc* . **52** 1263–334

[11] Yang W, Chen I H, Gludovatz B, Zimmermann E A, Ritchie R O and Meyers M A 2013 Natural flexible dermal armor *Ad. Ma e .* **25** 31–48

[12] Barthelat F 2007 Biomimetics for next generation materials *P. . T a . R. S c. Ma . . P. . . E . Sc* . **365** 2907–19

[13] National Institute of Standards and Testing 2008 *NIJ S a da d 0101.06—Ba . c Re . a ce, B d A ,* (www.ncjrs.gov/pdffiles1/nij/223054.pdf)

[14] Park J L, Chi Y S, Hahn M H and Kang T J 2012 Kinetic dissipation in ballistic tests of soft body armors *E. . Mec. .* **52** 1239–50

[15] Department of Defense 1997 *MIL-STD-662F: V50 Ba . c Te , A ,* (http://everyspec.com/MIL-STD/MIL-STD-0500-0699/MIL-STD-662F_6718/)

[16] Meyers M A, Lin Y S, Olevsky E A and Chen P-Y 2012 Battle in the amazon: arapaima versus piranha *Ad. . E . Ma e .* **14** B279–88

[17] 2018 *W. e R , —Ce a, . e t . t* (Utrecht: Rhino Resource Center) (www.rhinoresourcecenter.com/species/white-rhino/)

[18] Alerstam T 1987 Radar observations of the stoop of the peregrine falcon falco peregrinus and the goshawk accipiter gentilis *Ib .* **129** 267–73

[19] Weaver J C *e a* 2012 The stomatopod dactyl club: a formidable damage-tolerant biological hammer *Sc e ce* **336** 1275–80

[20] Jarman P J 1989 On being thick-skinned: dermal shields in large mammalian herbivores *B, . J. L . S c* **36** 169–91

[21] Jarman P J 1972 The development of a dermal shield in impala *J. Z, .* **166** 349–56

[22] Cave A J E and Allbrook D B 1959 The skin and nuchal eminence of the white rhinoceros *P, c. Z, . S c. L d.* **132** 99–107

[23] Geist V 1967 On fighting injuries and dermal shields of mountain goats *J. W d . Ma a* . **31** 192–4

[24] Shadwick R E, Russell A P and Lauff R F 1992 The structure and mechanical design of rhinoceros dermal armour *P. . T a . . R. S c.* B **337** 419–28

[25] Owen-Smith R N 1992 *Me a. e b e : T. e I t e ce, Ve La e B d S e, E ,* (Cambridge: Cambridge University Press) p 392

[26] Smalls L K, Randall Wickett R and Visscher M O 2006 Effect of dermal thickness, tissue composition, and body site on skin biomechanical properties *S Re . Tec , .* **12** 43–9

[27] Diridollou S *e a* 1998 An method for measuring the mechanical properties of the skin using ultrasound *U a, t d Med. B, .* **24** 215–24

[28] Shergold O A, Fleck N A and Radford D 2006 The uniaxial stress versus strain response of pig skin and silicone rubber at low and high strain rates *I . J. I ac E* . **32** 1384–402

[29] Neuman R E and Logan M A 1950 The determination of collagen and elastin in tissues *J. B, . C. e* . **186** 549–56

[30] Ridge M D and Wright V 1966 Mechanical properties of skin: a bioengineering study of skin structure *J. A . P. . , .* **21** 1602–6

[31] Purslow P P 1983 Measurement of the fracture toughness of extensible connective tissues *J. Ma e . Sc* . **18** 3591–8

[32] Wilhelm M and Bir C 2008 Injuries to law enforcement officers: the backface signature injury *F e . c Sc . I .* **174** 6–11

[33] Lanir Y and Fung Y C 1974 Two-dimensional mechanical properties of rabbit skin—I. Experimental system *J. B, ec. .* **7** 29–34

[34] Lanir Y and Fung Y C 1974 Two-dimensional mechanical properties of rabbit skin—II. Experimental results *J. B, ec. .* **7** 171–82

[35] Tong P and Fung Y-C 1976 The stress-strain relationship for the skin *J. B, ec. .* **9** 649–57

[36] Sherman V R, Tang Y, Zhao S, Yang W and Meyers M A 2017 Structural characterization and viscoelastic constitutive modeling of skin *Ac a B, a e .* **53** 460–9

[37] Hendriks F M, Brokken D, Van Eemeren J T W M, Oomens C W J, Baaijens F P T and Horsten J B A M 2003 A numerical-experimental method to characterize the non-linear mechanical behaviour of human skin *S Re . Tec , .* **9** 274–83

[38] Rodrigues L 2001 EEMCO guidance to the assessment of tensile functional properties of the skin *S P. a ac .* P. . , . **14** 52–67

[39] David N V, Gao X-L and Zheng J Q 2009 Ballistic resistant body armor: contemporary and prospective materials and related protection mechanisms *A . Mec. . Re.* **62** 050802

[40] Magat E E 1980 Fibres from extended chain aromatic polyamides *P. . T a . R. S c. Ma . P. . . E . Sc .* **294** 463–72

[41] Lane R A 2005 High performance fibers for personnel and vehicle armor systems: putting a stop to current and future threats *AMPTIAC Q* **9** 3–9

[42] Gosline J M, DeMont M E and Denny M W 1986 The structure and properties of spider silk *E dea, t* **10** 37–43

[43] Gosline J M, Guerette P A, Ortlepp C S and Savage K N 1999 The mechanical design of spider silks: from fibroin sequence to mechanical function *J. E . B, .* **202** 3295–303

[44] Nova A, Keten S, Pugno N M, Redaelli A and Buehler M J 2010 Molecular and nanostructural mechanisms of deformation, strength and toughness of spider silk fibrils *Na , Le .* **10** 2626–34

[45] Cranford S W, Tarakanova A, Pugno N M and Buehler M J 2012 Nonlinear material behaviour of spider silk yields robust webs *Na t e* **482** 72–6

[46] Morye S S, Hine P J, Duckett R A, Carr D J and Ward I M 2000 Modelling of the energy absorption by polymer composites upon ballistic impact *G , . . Sc . Tec. , .* **60** 2631–42

[47] Naik N K, Shrirao P and Reddy B C K 2006 Ballistic impact behaviour of woven fabric composites: formulation *I . J. I ac E* . **32** 1521–52

[48] Cunniff P M 1992 An analysis of the system effects in woven fabrics under ballistic impact *Te Re . J.* **62** 495–509

[49] Duan Y, Keefe M, Bogetti T A, Cheeseman B A and Powers B 2006 A numerical investigation of the influence of friction on energy absorption by a high-strength fabric subjected to ballistic impact *I . J. I ac E* . **32** 1299–312

[50] Lee Y S, Wetzel E D and Wagner N J 2003 The ballistic impact characteristics of Kevlar®

[99] Grujicic M, Glomski P S, He T, Arakere G, Bell W C and Cheeseman B A 2009 Material modeling and ballistic-resistance analysis of armor-grade composites reinforced with high-performance fibers