Article:

Johnson, A.J., Bingham, G.A. and Majewski, C. orcid.org/0000-0003-3324-3511 (2018) The design and assessment of bio-inspired additive manufactured stab resistant armour. Virtual and Physical Prototyping, 13 (2). pp. 49-57. ISSN 1745-2759

https://doi.org/10.1080/17452759.2017.1369438

The design and assessment of bio-inspired Additive Manufactured stab resistant armour

A. A. Johnson[1*], G. A. Bingham[1], C. E. Majewski[2]

[1]*Loughborough Design School, Loughborough University, Loughborough, United Kingdom.*

[2]*Department of Mechanical Engineering, The University of Sheffield, Sheffield, United Kingdom.*

*Corresponding author email: a.johnson@lboro.ac.uk

A.A. Johnson is a lecturer in Product and Industrial Design within the Loughborough Design School at Loughborough University. Dr. Johnson is a leading authority in the area of design and utilisation of Additive Manufacturing technologies for high performance protective applications. ORCID ID: 0000-0002-9418-0545

G.A. Bingham is a senior lecturer and programme director in Product Design within the Loughborough Design School at Loughborough University. He is an internationally recognised researcher in the field of Additive Manufacturing, a leading authority in the area of Design for Additive Manufacturing, and a recognised expert in the area of Additive Manufactured textile design, modelling and application. ORCID ID: 0000-0002-6971-033X

C.E. Majewski is a lecturer in Mechanical Engineering at The University of Sheffield, and a founding member of the University's Centre for Advanced Additive Manufacturing (AdAM). Her ability to conduct world class research in Additive Manufacturing was recognised when she was awarded the 2011 International Outstanding Young Researcher in Freeform and Additive Manufacturing. ORCID ID: 0000-0003-3324-3511

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The performance of modern fibre-based or Polycarbonate armour has significantly progressed since their introduction, providing protection against a range of low and high velocity threats. While this is so, users of such armour frequently report of issues relating to their operational suitability resulting in impaired performance and physiological effects. Recently researchers have focussed on how naturally occurring protective mechanisms could be utilised to enhance the protective and operational performance of wearers of engineered body armour. The research presented within this paper therefore utilises a series of key design characteristics exhibited within naturally occurring elasmoid scale armour, coupled with established Laser Sintering manufacturing parameters, for the realisation and assessment of a scale-based stab resistant armoured structure to internationally recognised test standards.

Keywords: Body armour; Stab resistance; Selective laser sintering; Computer aided design; Bio-inspiration

1. Introduction

The development of armour, whether in nature or engineered, is driven by one essential objective – the desire to "maximise battlefield survivability and mobility" (Arciszewski and Cornell 2006). This is typically achieved by either optimising energy absorption, dissipation and freedom of movement, and/or minimising deformation and penetration (Crouch 2016).

Current stab resistant body armour is typically manufactured from Polycarbonate to create a non-flexible breast plate structure (PPSS Group 2017). Whilst the protective performance of these articles have progressed since their introduction, users of such armour frequently report of ill-fitting and uncomfortable use. This, combined with their high weight and low breathability, at best results in impaired performances such as reduced running speeds or operational manoeuvrability, and at worst can lead to physiological effects including nerve damage and severe musculoskeletal injuries (Konitzer *et al.* 2008, Teng *et al.* 2008, Larsen *et al.* 2011, Dempsey *et al.* 2013).

In an attempt to enhance the design and development of the next generation of body armour, researchers have studied the mechanical performance of biological scale armour in animals such as armadillos, alligators, and fish (Arciszewski and Cornell 2006). One of the most common predatory attacks these animals must endure is a localised impact from a sharp object such as a tooth, in which high stress concentrations have the potential to cause catastrophic failures within their natural armour system (Yang, Chen, *et al.* 2013). Such armours must also minimise back-face deformation by appropriately dissipating impact energies to avoid causing injuries to underlying soft tissue and vital organs (Song *et al.* 2011, Yang, Chen, *et al.* 2013). These are typically achieved by: (Song *et al.* 2011)

- Deforming and/or fracturing the penetrating threat.
- Dissipating the penetrative energy via deformation and/or cracking the armour.
- A combination of the previous two mechanisms.

One form of biological armour used to achieve protection is through the use of scale-based structures such as ganoid or elasmoid scales, examples of which are shown within Figure 1.

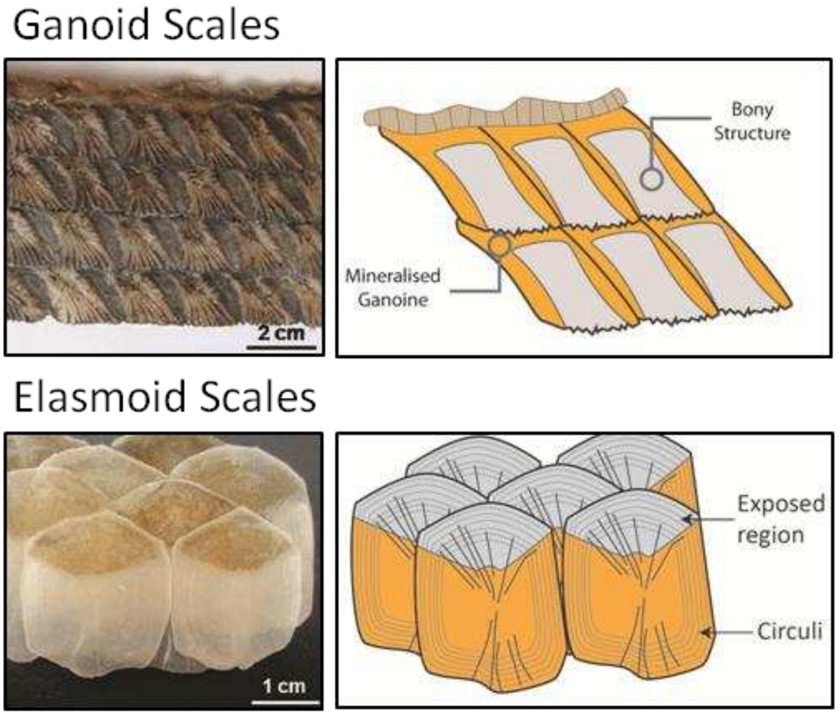


Figure 1: Examples of Ganoid and Elasmoid scales (Yang, Chen, *et al.* 2013)

While individual scales are often unable to provide adequate protection, once assembled as part of a hierarchical imbricated (overlapping) structure, scale assemblies have been shown to *"exhibit improved mechanical properties"* (Allison *et al.* 2013) and provide a level of flexibility suitable to the needs of its respective animal (Zhu *et al.* 2012, Yang, Chen, *et al.* 2013, Yang, Gludovatz, *et al.* 2013).

A number of geometric parameters have also been shown to govern the structure of an imbricated elasmoid scale assembly. These are presented within Figure 2 and include: (Browning *et al.* 2013)

- Total scale length (Ls)
- Scale orientation angle relative to tissue (Θ)
- Scale thickness (Ts)
- Exposed scale length (d)
- Distance between scales (Td)

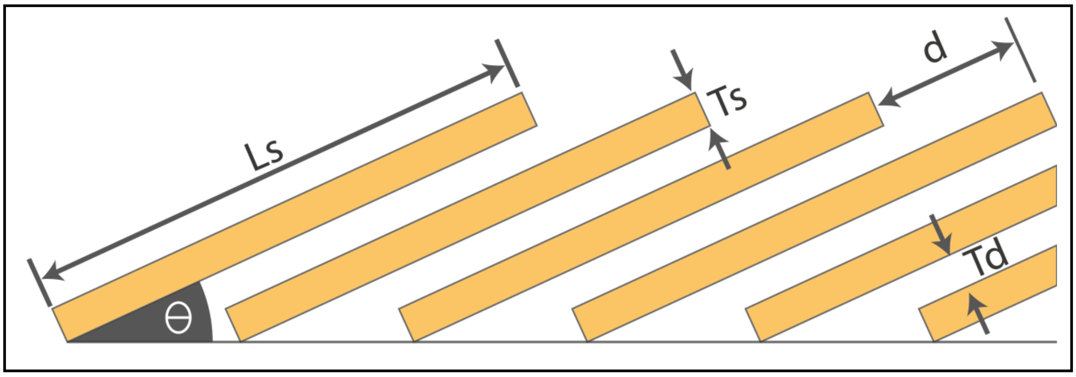


Figure 2: Structural overview & geometric parameters governing the elasmoid scales [22]

By varying characteristics such as the scale angle (Θ) and the exposed scale length (d), the distance between the individual scales (Td) can change (Browning *et al.* 2013). It is also therefore possible to determine a value for the degree of scale overlap, also known as the imbrication factor (Kd), where: Kd = d/Ls (Browning *et al.* 2013). Calculating the imbrication factor enables armour to be classified by their potential level of protection. Where a Kd value is returned close to one, research suggests that a low level of scale overlap is present and therefore the imbricated assembly is classified as a light armour (Browning *et al.* 2013). Conversely, where a Kd value close to zero is returned this typically demonstrates a high degree of overlap and could therefore be considered to be heavily armoured (Browning *et al.* 2013).

One group of technologies that have shown the potential to efficiently realise highly complex linkable textile-like geometries is that of Additive Manufacturing (AM). AM textiles are increasing in popularity with the majority of which focussed around their use for fashion purposes (Herpen 2012, 3D-Fashion 2017, Peleg 2017). A small degree of research has however focussed on more demanding applications such as the use of AM technologies to mimic fish scales (Bruet *et al.* 2008), to assess flexibility - thereby not taking into account the full capabilities of AM techniques for the production of high performance protective assemblies.

Prior research has also been performed to establish a series of manufacturing characteristics for stab resistive assessment of planar Laser Sintered specimens (Johnson 2014, Johnson *et al.* 2015, 2017). These structures successfully demonstrated protection to the world leading United Kingdom (UK) Home Office Centre for Applied Science and Technology (CAST) stab resistant KR1-E1 impact energy of 24 Joules across both single thickness and dual layered planar structures manufactured from a 50/50 mix of virgin and recycled DuraformEX® (Johnson *et al.* 2015). This previous research therefore demonstrated comparable protective properties to traditional rigid PC-based stab resistant solutions currently used by a front-line emergency service personnel.

As previously noted, scale based natural armour when arranged in an imbricated assembly can create a hierarchical structure capable of providing effective levels of protection against localised threats whilst minimising back face deformation. While initial progress has been made in terms of utilising AM technologies to achieve stab resistance using planar structures, further research is required to translate these findings to progress towards the development of a wearable protective article. As such, the research presented within this paper therefore utilises the outlined biological scale design principles to inform the design and development of a modern imbricated scale-based armour solution capable of providing protection to the UK CAST KR1-E1 stab resistant impact energy of 24 Joules and realised via Laser Sintering.

2. Design Methodology and Scale Development

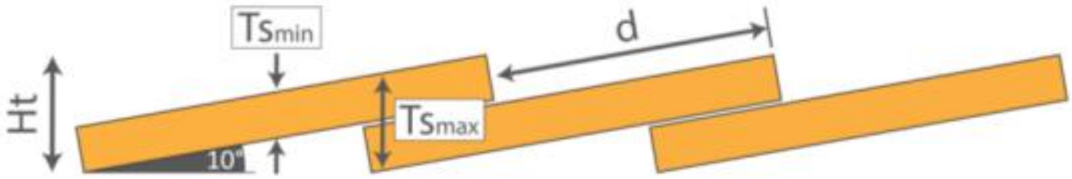
A number of design activities fundamental to the development of a suitable bio-inspired scale-based imbricated structure are outlined. These activities include identifying the optimal scale assembly angle, as well as exploring methods to maintain protective coverage between the discrete scale-like geometries.

2.1. Establishing scale imbrication angle

Prior research has suggested that an assembly angle between 10°-20° enables discrete elements, such as scales, to form a multi-layered protection mechanism. Using previously defined planar specimens measuring 40 x 40 x 4.5mm, assembly angles ranging between 10°-20° were visually assessed to ascertain an appropriate angle to achieve an imbricated two layered protective structure - the 10° imbricated example is shown within Table 1.

Table 1: Planar assembly at 10° assembly angle

Assembly Angle	**Total Assembly Height (Ht)**	**Overlap Distance (d)**	**Minimum Thickness (Ts_{min})**	**Maximum Thickness (Ts_{max})**	**Imbrication Factor**
10°	11.38 mm	27.22 mm	4.57 mm	9.44 mm	0.681

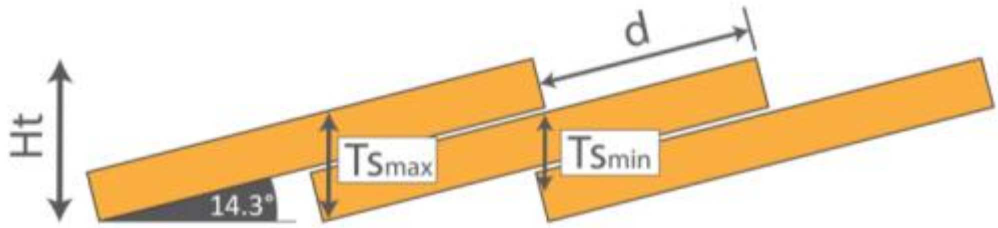


Upon review of the imbricated concept at 10°, dual layered coverage with a minimum thickness (Ts_{max}) of 9.00 mm across two layers was unable to be maintained. The minimum thickness (Ts_{min}) achieved at 10° was estimated at 4.57mm across a single layer of protection. Further investigation was therefore performed to establish a minimum Ts_{min} value of 9.00mm across a two layered structure. Additional assembly angles of 11°-20° increasing in one degree increments were initially analysed - the results of which are outlined within

Table 2.

Table 2: Planar assembly at 10-20° assembly angles

Assembly Angle	**Total Assembly Height (Ht)**	**Overlap Distance (d)**	**Minimum Thickness (Ts_{min})**	**Maximum Thickness (Ts_{max})**	**Imbrication Factor**
10°	11.38 mm	27.22 mm	4.57 mm	9.44 mm	0.681
11°	12.05 mm	24.69 mm	4.58 mm	9.47 mm	0.617
12°	12.72 mm	22.58 mm	4.60 mm	9.51 mm	0.565
13°	13.38 mm	20.79 mm	4.62 mm	9.54 mm	0.520
14°	14.04 mm	19.25 mm	6.18 mm	9.58 mm	0.481
14.1°	14.12 mm	19.12 mm	7.03 mm	9.58 mm	0.478
14.2°	14.17 mm	18.97 mm	8.19 mm	9.59 mm	0.474
14.3°	14.24 mm	18.83 mm	9.32 mm	9.60 mm	0.471
14.4°	14.31 mm	18.69 mm	9.60 mm	10.50 mm	0.467
14.5°	14.37 mm	18.56 mm	9.61 mm	11.50 mm	0.464
15°	14.69 mm	17.91 mm	9.63 mm	14.60 mm	0.448
16°	15.35 mm	16.74 mm	9.67 mm	14.67 mm	0.419
17°	16.00 mm	15.70 mm	9.72 mm	14.74 mm	0.393
18°	16.64 mm	14.77 mm	9.78 mm	14.83 mm	0.369
19°	17.28 mm	13.94 mm	9.84 mm	14.91 mm	0.349
20°	17.91 mm	13.19 mm	9.90 mm	15.00 mm	0.330



From this initial investigation it was highlighted that an estimated Ts_{min} value of 9.63mm could be established at an assembly angle of 15° - satisfying the 9.00mm minimum thickness as outlined by previous research for dual layered stab protection. It should also be noted that within this same assembly the Ts_{max} value was estimated to be 14.60mm. Further investigations were therefore performed that sought to reduce the Ts_{max} value whilst ensuring a Ts_{min} value of at least 9.00mm was maintained throughout the protective structure. During this phase a series of imbricated planar structures ranging in assembly angles from 14.1-14.5° increasing in 0.1° increments were assessed to identify an optimal assembly angle, the results of which are outlined within

Table 2.

It was therefore determined that an assembly angle of 14.3° suitably established a Ts_{min} value of 9.32mm and a Ts_{max} value of 9.60mm – a 1.60mm reduction in the maximum thickness initially established for the 15° imbricated assembly.

2.2. Maintaining protective coverage

While discrete planar elements arranged at a 14.3° assembly angle have been shown to possess the potential to provide suitable dual layered coverage, inherent weaknesses exist between the individual elements where little or no protection is provided - as highlighted within Figure 3**.**

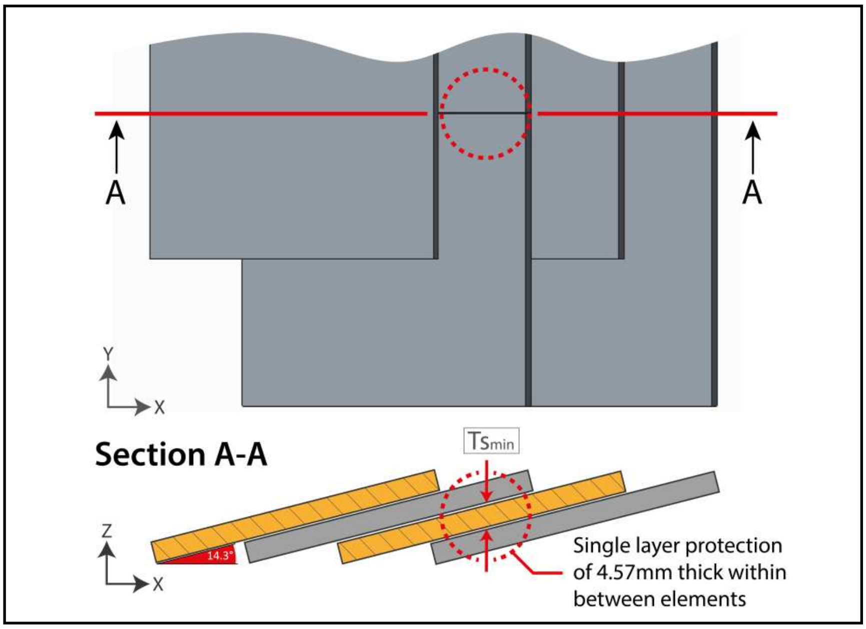


Figure 3 : Highlighting single layer weaknesses between elements

By utilising imbricated planar elements, a single layer of protection was identified in the region between individual elements which could potentially allow a bladed threat to circumnavigate the dual layered protection mechanism and therefore inflict injury. In light of the highlighted weakness, coupled with the presented evidence of utilising naturally occurring scale based armours and the manufacturing freedoms enabled my AM technologies, a new scale-like protective geometry was established that provided maximum coverage across the complete assembly whilst adhering to the established minimum protective requirements for dual layered LS structures, the initial proposal of which is shown within Figure 4 (left).

When orientated with an imbrication assembly angle of 14.30°, each element was designed to sit on top of those below. This therefore encouraged the formation of an interlinking structure with the aim to enhance stab resistance and ensure an effective area for stab energy dissipation was created across the complete assembly. A spacing of 0.30mm between elements was established to assist with assembly manufacture. One of the primary aims of the initial proposal presented within Figure 4 (left) was to enhance protective coverage between assembled elements and to therefore assist in creating a dual layered structure across the complete imbricated assembly. Enhancing coverage between individual elements was therefore achieved by featuring a durable core as inspired by ganoid based biological armour where such armours typically feature elements with raised central regions. The established initial concept also featured a dual layered structure within each discrete element where imbricated scales do not overlap – this is realised through the utilisation of Additive Manufacturing technologies. Once assembled, the individual elements establish a dual layered imbricated structure measuring 9.03mm in thickness across the rear of each element.

Further development of a number of design features, namely the top/strike face geometry, within the initial scale-like concept was required in order to minimise its 14.50mm orientated Ts_{max} value and total imbricated assembly thickness of 19.33mm. The enhanced proposal is also shown within Figure 4 (right).

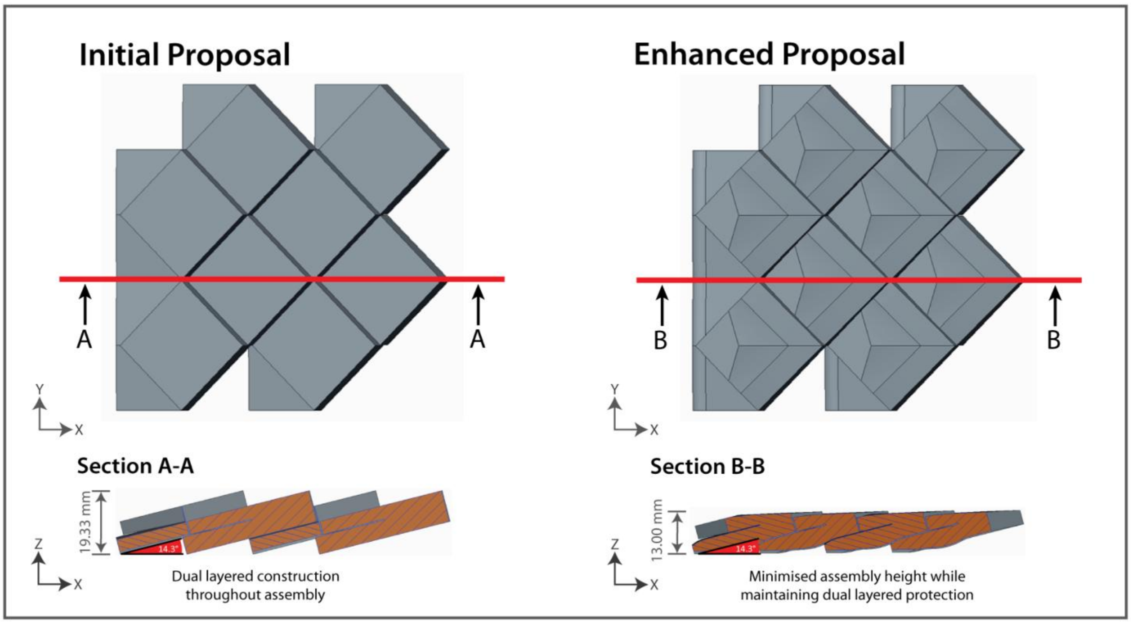


Figure 4: Initial (left) and enhanced (right) scale design proposals

Further enhancements to the geometry of the individual scale-like elements enabled the overall assembly height to be reduced by over 33% from 19.33mm to 13.00mm - whilst ensuring a dual layered structure with a Ts_{min} value equal to or greater than 9.00mm was maintained. A summary of the final scale-like individual element design and overall assembly are outlined within Table 3**.**

Table 3: Link and assembly design characteristics

	Characteristic	**Link Parameter**
Individual Element	Morphology	Pentagonal
	Length	40.00 mm
	Width	40.00 mm
	Maximum thickness	10.30 mm

	Minimum thickness	4.50 mm
	Strike surface chamfer	78.00°
Assembly	Assembly Angle	14.30°
	Imbrication Factor	0.496
	Spacing between Scales	0.30 mm
	Minimum thickness	9.42 mm
	Maximum thickness	13.00 mm

The final scale-like concept featured a pentagonal morphology, an integrated dual layered construction with an assembled minimum thickness of 9.42mm, and a 78.00° chamfer upon its strike surface to minimise the total thickness of the complete imbricated assembly. As the proposed stab resistant imbricated concept was largely developed based on prior materials experimental testing, there was a requirement to assess the protective performance of a series of manufactured imbricated structures against established stab resistant standards.

3. Experimental Methodology

This section documents the experimental methodology used for the manufacture and subsequent validation of the identified stab resistant scale design characteristics and developed protective solution.

3.1. Test Specimen Geometry

To facilitate the manufacture and assessment of the imbricated specimen assemblies, a retaining structure was incorporated within the assembly geometry thus enabling the individual protective elements to be securely positioned within the imbricated structure, as shown within Figure 5.

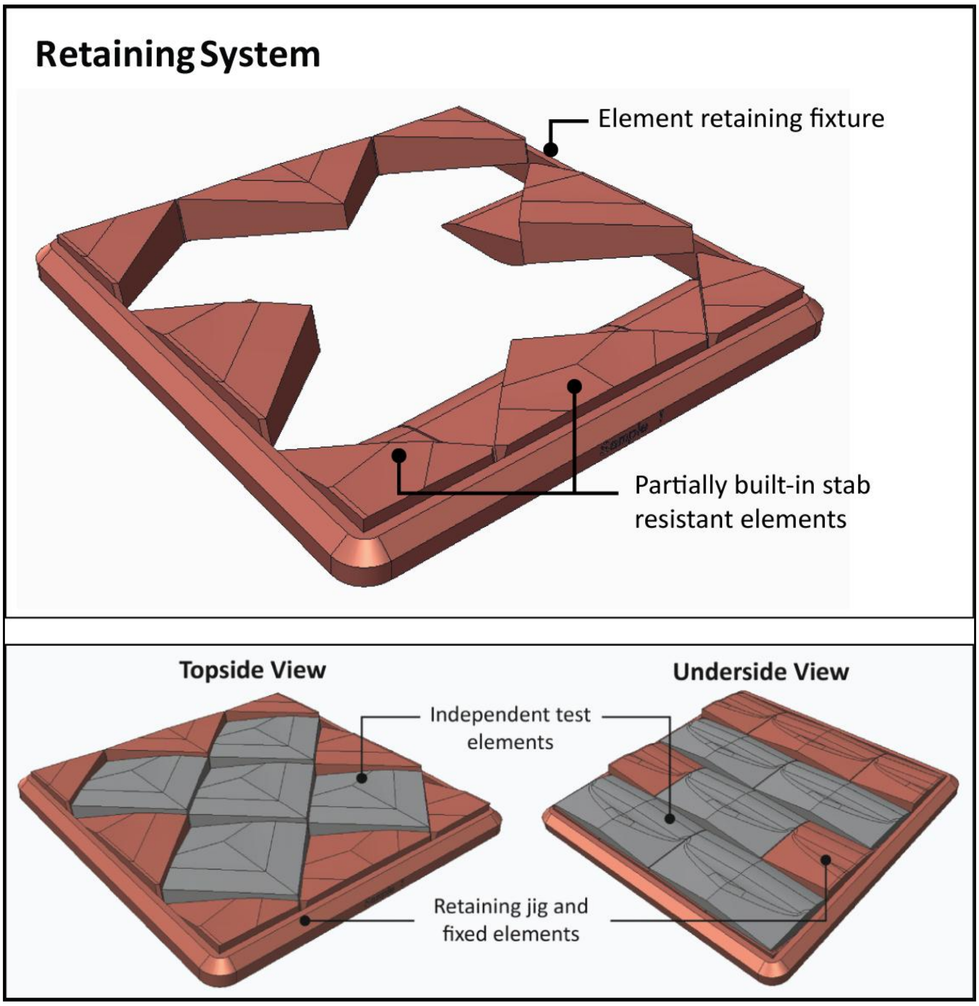


Figure 5: Test assembly featuring individual scale elements ad retaining structure

The test assemblies featured five independent elements; with a further eight constrained elements manufactured within the retaining perimeter structure. This method was adopted to ensure a thorough assessment of the protective performance of the engineered scale-like elements was performed prior to the integration of a linkable mechanism.

3.2. Build Material and Process Parameters

All test specimens were manufactured from a 50/50 mix of virgin and recycled Duraform EX® using an EOS P100 Formiga Laser Sintering machine and previously optimised process parameters - as documented within Table 4 (Johnson *et al.* 2015).

Table 4: Manufacturing process parameters

Laser Sintering Process Parameter	Duraform EX® (50/50 mix)
Layer thickness	0.1mm
Part bed temperature	178.5°C
Laser Power	22W
Scan Speed	3,000 mm/s (3.0 m/s)
Warm-up time	300 minutes

3.3. Build Location

In total three imbricated assembly architectures and a further three control dual layer planar test specimens with a total thickness of 9.00mm were manufactured. Both imbricated assemblies and planar specimens were randomly positioned within the LS build volume to minimise any potential effects on stab resistive performance – their respective positions are documented within Figure 6**.**

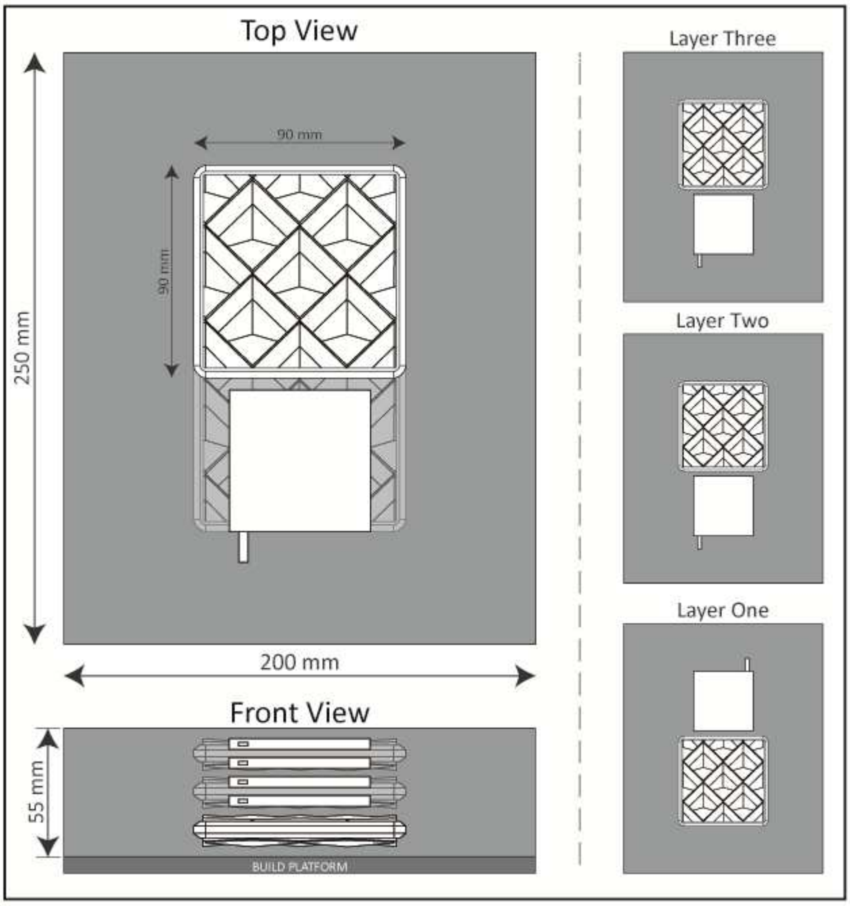


Figure 6: Test specimen build location within EOS P100 Laser Sintering machine

All test specimens and imbricated assemblies were centrally located on the build platform of the EOS P100 Formiga LS machine. Spacing between components was maintained at 5.00mm in both X and Y-directions, while 3.00mm spacing was used between specimens in the Z-direction - the total build height measured 55mm.

3.4. Stab Testing Experimental Design

All manufactured specimens were stab tested to the UK CAST KR1-E1 impact energy using an Instron 9250HV drop tower with Stanley 1992 Trimming Blades with an established operational procedure (Johnson 2014). The order in which the manufactured specimens were tested was randomised to minimise experimental biases. Planar specimens were stab tested in the middle of their strike face, while imbricated assemblies were positioned to ensure test blades made contact within their central region – as depicted in Figure 7**.**

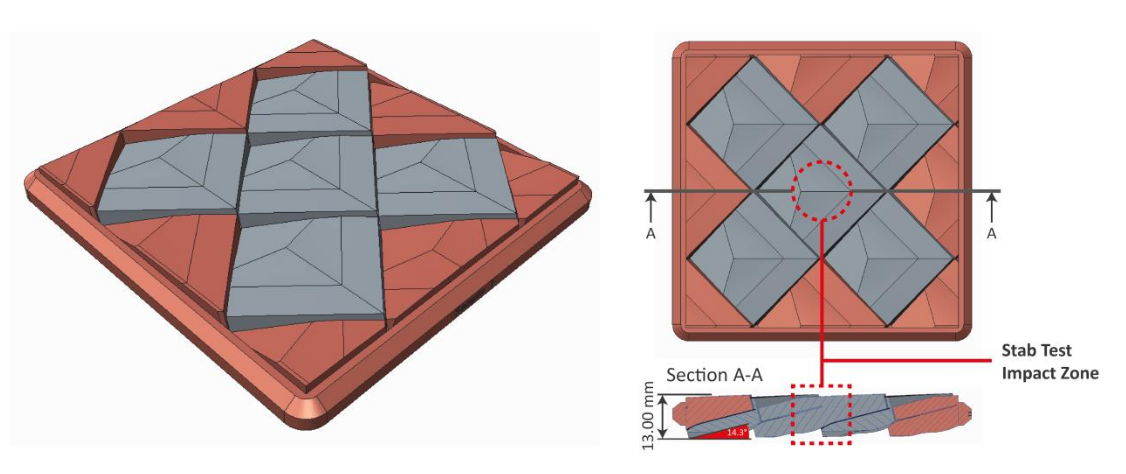


Figure 7: Imbricated assembly stab test impact location

A central stab region on the imbricated assemblies was identified as it was determined that this region enabled full assessment of the protective performance of both the dual layered mechanism comprising of two individual elements, as well as that of a single element featuring the dual layered structure. Cross-sectional analysis of the imbricated assembly, as shown within Figure 7, also ensured that the dual layered structure was maintained throughout.

4. Results

All tests demonstrated successful levels of stab resistance, below the 7.00mm permissible limit as defined by the CAST KR1 body armour standard, therefore validating the established protective design scale-based characteristics previously outlined within Table 3. A summary of the test results are presented within Table 5.

Table 5: Stab test results summary

No.	Specimen ID	Test Order	Penetration Depth (mm)	Result
1	Imbricated Assembly One	3	0.00	Pass
2	Imbricated Assembly Two	1	5.38	Pass
3	Imbricated Assembly Three	6	0.00	Pass
4	Planar One (Control)	4	0.00	Pass
5	Planar Two (Control)	5	1.98	Pass
6	Planar Three (Control)	2	0.00	Pass
Mean Impact Energy: 23.66 J				
Mean Impact Velocity: 2.70 m/s				

Upon review of Table 5 it can be stated that the planar control specimens included within this experiment verified stab resistance in-line with previously published outcomes. Experimental results also documented that blade penetration in all three of the imbricated assemblies were below the CAST 7.00mm maximum – with two assemblies featuring zero blade penetration. Imbricated Assembly Two demonstrated the highest level of blade penetration across all three test assemblies with a depth of 5.38mm, as shown in Figure 8.

Figure 8: Measuring blade penetration on Imbricated Assembly Two.

It should also be noted that in all tests the impacting blade shattered, leaving no additional damage to the AM scale elements - a mechanism previously outlined by *Song et al. 2011* in which deforming and/or fracturing the penetrating threat is one of three methods to maintain protection. In addition, no damage was shown to have been caused to the underside of the impacted structures as a result of testing. Elements from the test assemblies did however demonstrate deformation into the clay backing material trays, as shown within Figure 9.

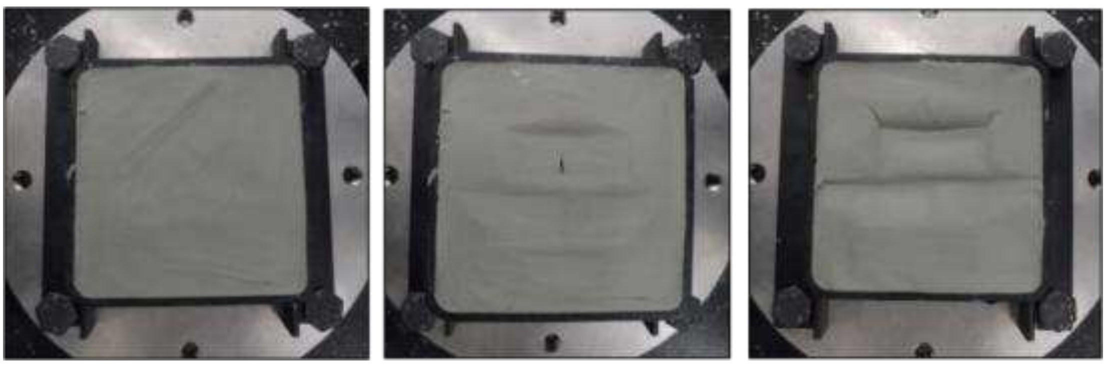


Figure 9: Backing material deformation signatures for imbricated assembly tests one (left), two (middle) and three (right)

Whilst the degree of back face deformation appears to have been minimal and evenly spread across the impacted area and surrounding elements with assemblies one and two, the backing material within 'Imbricated Assembly Three' had a notably stronger back face deformation signature. This deformation was measured at 6.50mm and therefore fell within the maximum 15.00mm permissible limit as defined by the CAST Blunt Trauma Protector standard (Malbon 2007).

5. Discussion & Conclusion

This body of work has demonstrated the successful identification, development, and subsequent validation of a number of key bio-inspired and technology driven design and manufacturing characteristics, for the realisation of stab resistant Laser Sintered scale-like armour to the industry leading UK CAST KR1-E1 impact energy of 24 Joules - as used by existing body armour manufacturers.

Such key design criteria include, identifying an optimal 14.30° assembly angle for scale imbrication, and establishing a dual layered structure within discrete scale elements and across a complete imbricated architecture. A complete list of discrete link and assembly design characteristics are presented within Table 3.

While the total assembly thickness measured 13.00mm, the established design characteristics ensured that a minimum 9.42mm thickness was maintained across the complete dual layered imbricated assembly utilising individual elements of a pentagonal morphology measuring approximately 40 x 40 mm in length and width. This marks a substantial improvement from the 80 x 80mm size used for the testing of planar specimens in previously published research. By achieving this significant reduction in size, coupled with the utilisation of the identified design characteristics, progress is being made towards the realisation of a more manoeuvrable and operational conducive protective solution in comparison to existing rigid stab resistant solutions that have been shown to negatively impact the operational and health performance of its wearer.

In addition, the results presented within this paper further support existing literature that scale-based imbricated structures featuring a comprehensive dual layered level of protection realised via AM technologies may have the potential to begin addressing the long standing conflict between establishing body armour suitable for both survivability and maximum user mobility and comfort.

While the key requirement for this study was to validate the protective performance of a number of bio-inspired scale design criteria, it is recognised that additional investigations would be required to further develop methods of appropriately linking the developed scale-like elements to create a truly textile-like assembly and therefore facilitate further assessment in terms of flexibility and operational suitability against existing well-established protective solutions. The presented newly established design characteristics outlined within this paper also provides a platform for a range of further development opportunities to be performed within the outlined research domain, including:

(1) To investigate suitable linking mechanisms to establish an articulated AM protective assembly.
(2) A structured Design of Experiments optimisation and response surface analysis to determine the relationship between the established design characteristics and impact on protective performance and articulation/manoeuvrability.
(3) Assess post-processing opportunities to enhance the protective and operational performance of LS armour.
(4) Identify and trial the process of generating bespoke protective solutions.
(5) Seen to enhanced the levels of protection including against high velocity threats.

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