Book chapter :
O'Sullivan, R., Rees, A., Griffiths, C. & Wadlinger, J. (n.d). *A Study on the Modeling and Simulation of Bio-inspired Hedgehog Spines Structures for More Efficient Use Digital Manufacturing Processes.* Peter Ball, Luisa Huaccho Huatuco, Robert J. Howlett, Rossi Setchi (Ed.), Sustainable Design and Manufacturing 2019, (pp. 375-385). Singapore: Springer Link.
http://dx.doi.org/10.1007/978-981-13-9271-9_31

A study on the modelling and simulation of bio-inspired hedgehog spines structures for more efficient use digital manufacturing processes

R. O'Sullivan[1], A. Rees[1], C.A. Griffiths[1], J. Wadlinger[2]

[1]College of Engineering, Swansea University, Swansea, UK
[2] Karlsruhe Institute of Technology (KIT), Germany

Abstract.
Direct digital manufacture and additive manufacture have allowed designers the ability to design components without the design limitations witnessed in subtractive manufacturing process routes. In particular, designers can now design parts that fully utilise material usage resulting in a more sustainable and environmentally friendly application of manufacturing technology. Within this context designing and manufacturing bioinspired components has the potential to increase both component functionality and optimise material usage. One such area of biomimicry with advantageous strength-to-weight ratio can be found in hedgehog spines. Within this study hedgehog spines were re-designed to facilitate production through additive manufacture. In addition, with the use of finite element analysis to quantify the resulting compressive characteristics the optimal internal geometry and septa spacing was determined. Also, a Design of Experiments study was conducted to determine which design features have the greatest influence on the resulting stress in the spine. The analysis concluded that the combination of longitudinal stiffeners and equally spaced septa give the spine its superior compressive strength.

Keywords: biomimicry; hedgehog spines; Additive manufacture; digital manufacturing

1 Introduction

The term 'biomimetics' was first used in the 1950's by Otto Smith, a biophysicist and bio-engineer who attempted to produce a device that mimicked the electrical impulse of a nerve [1]. However, the concept of biomimicry has been around for centuries; for example, Leonardo Da Vinci's design for a 'flying machine' mimicked the flight of winged animals such as bats and birds in the fifteenth century. Examples of how biomimicry is being used today include; Velcro® which replicates the tiny hooks of Burdock seeds, honeycomb structures are used to maintain the strength of a material whilst reducing the amount of material used, swimsuits that mimic the aerodynamic properties of sharkskin and needles comprising a central straight needle and two outer jagged ones that mimic mosquito mouths to glide painlessly into the skin [2]. There is a large amount of diversity in natural structures, from the tensile strength displayed by spiders' silk and an Abalone shells ability to absorb large impacts, to the super hydrophobicity of lotus leaves [3].

Some of the properties displayed in nature come from chemical or biological processes. However, this study will focus purely on the physical properties of biological structures. Hedgehog spines have a high strength-to-weight ratio with their main function most likely being shock absorption, as they can resist buckling up to 200 times their critical load [4]. The unique internal structure of these spines is thought to be the key to their strength and bio-mimicking it has many potential shock absorbing applications.

2 Biomimetic

2.1 Hedgehog Spines

In the study by Vincent it was concluded that both hedgehog spines and porcupine quills both consist of pointed tubes made from the fibrous alphaprotein keratin [5]. In the case of porcupine quills they differ in length across the body and are relatively easy to remove. Hedgehog spines are typically embedded into the skin and slightly curved in geometry. The porcupine's quills main function is defense, whilst in comparison the hedgehog spines main functions is shock absorbing, as hedgehogs bounce when they fall [5].

Hedgehog spines structures consist of an outer tube-shaped wall with orthogonal longitudinal and circumferential stiffeners in a 'square honeycomb structure'. There is a foam-like structure located down the center to support the outer walls from local buckling. This structure means that compared to hollow tubes, the spines are three times better at resisting buckling under axial load [5].

When designing hedgehog spines for a given bending stiffness, the mass of the tube could be reduced by increasing the relative radius, giving the tube a higher second moment of area, and therefore greater flexural rigidity. However, the tube would undergo Brazier ovalisation at the point of highest force, but the longitudinal and circumferential stiffeners provide reinforcement, and if they were increased in size, the foam core could be removed. The material in the center of the core had a low second moment of area and provides very little support in proportion to its mass, meaning it can safely be omitted from the structure [5].

Fig. 1 displays the spines from a female African Pygmy Hedgehog [6]. The air pockets along the core of hedgehog spines, separated by regularly spaced septa and other internal structures, delay the onset of buckling under axial loads, enabling the spines to absorb large amounts of mechanical energy [7]. The septa delays the onset of local buckling by retaining the cross-section, making the second moment of area higher. In addition, the septa resist tension rather than compression, as they are thin enough to buckle in compression. Once the load is large enough to cause a section of the spine to become oval, the effect of the second moment of inertia is reduced, and the spine fails due to local buckling or compression failure [7].

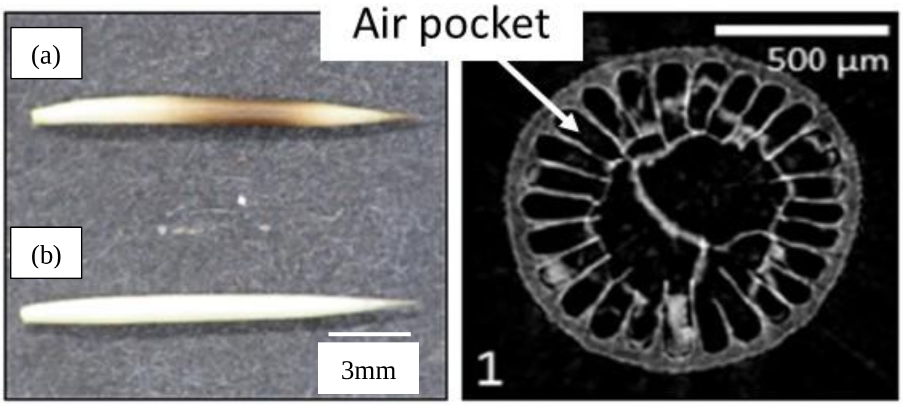

Fig. 1. (a) Spines and (b) microscopic view of spines from a female African Pygmy Hedgehog [6]

In a study by Kennedy et al., it was concluded that hedgehog spines are gram for gram stronger than certain grades of stainless steel for rods of the same diameter (1mm) and as pliable as styrene rods of a slightly larger diameter. This combination of strength and elasticity, as well as being lightweight and material efficient makes hedgehog spines good shock absorbers, with biomimetic potential [6].

The research in this paper is a starting point for the creation of a knowledge repository with focus on the applicability of bioinspired structures to aid design functionality and deliver more sustainable products due to optimized material usage. The paper is organized as follows. Section 3 discusses the model configuration and Finite Element Analysis (FEA) setup. In section 4, the results are discussed. Finally, in section 5, the main conclusions from the conducted study are presented.

3 Experimental setup

3.1 Model Development

SolidWorks was used to both 3D model and perform the subsequent FEA simulation. The initial model was based on the diagram in Fig. 2. To simplify its geometry the dimensions were taken from indicative values from previous research studies [4, 5-7]. The dimensions are presented in Table 1. Initially FEA was attempted on the simplified replica design, however the model was unable to mesh due to length scale integration challenges in the simulation software. Therefore, the initial model was scaled-up by a factor of 100 to facilitate meshing. The model also contained fillets between the intersection of the septa and the tube wall to reduce stress raisers and to more accurately replicate real hedgehog spines. The material used for the simulations was PLA and the properties are presented in Table 2.

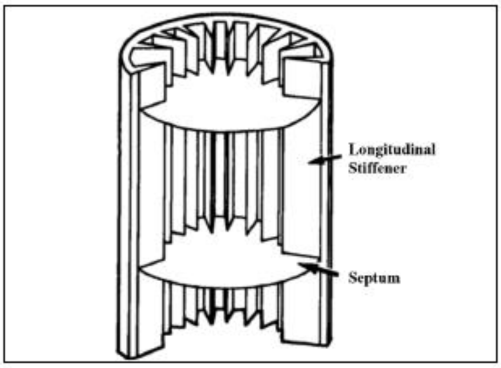

Fig. 2. Simplified spine diagram [9]

Table 1. Hedgehog spine dimensions (African Pygmy) [4]

Spine length (mm)	**Spine Outer Diameter (mm)**	**Wall Thickness (mm)**	**Longitudinal Stiffener Length (mm)**	**Longitudinal Stiffener Width (mm)**	**Septum Thickness (mm)**	**Septum Spacing (mm)**	**Number of longitudinal stiffeners**
20	1	0.045	0.184	0.015	0.020	0.217	25

Table 2. Material properties of PLA

Material	**UTS (MPa)**	**Strain at failure**	**E (MPa)**
PLA	47.66	0.04	3414

For the FEA a static simulation was set-up with one end of the spine fixed in all directions and a compressive force applied at the other end. The compressive force was increased in regular intervals from 1kN to 100kN. This test was then repeated with the longitudinal stiffeners and the evenly spaced septa removed individually and together, so that their isolated effects on the spine could be assessed.

The FEA studies were also repeated on standard tubing geometries for benchmarking study purposes.

3.2 Mesh Refinement

To ensure the FEA on the spine was not mesh dependent, the optimum mesh was found through mesh refinement. This was done by running multiple simulations and reducing mesh size each time, until the difference in the maximum stress was negligible between runs. The graph in Fig. 3 illustrates the results of curvature based meshes ranging from 15 to 5mm. The results begin to plateau around a minimum element size of 7mm, therefore this mesh size was chosen for the study.

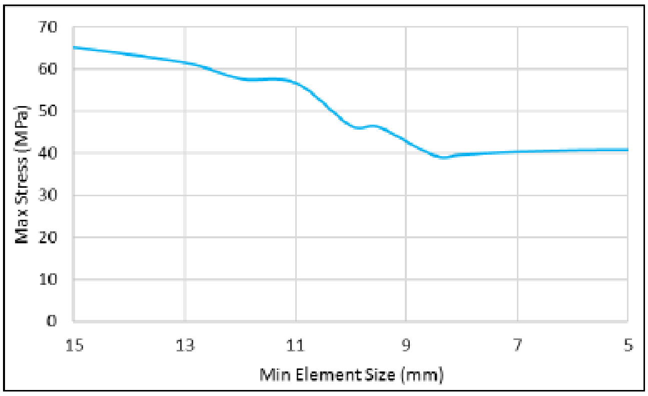

Fig. 3. Mesh Refinement

3.3 Factorial Analysis

A full factorial design of experiment (DOE) was conducted to determine which factors/interaction of factors have the greatest influence on the mechanical properties of the spine. Table 3 displays the factors and levels of the parameters analyzed in the study. The model was set up with a compressive force of 425 kN.

Table 3. FACTORS USED FOR FULL FACTORIAL ANALYSIS

Factor	Level	
	-1	1
A. Wall Thickness (mm)	4.5	6.5
B. Number of Stiffeners	15	20
C. Stiffener Thickness (mm)	16.8	25
D. Septum Spacing (mm)	60	100

4. Results and Discussion

4.1 Initial FEA

Fig. 4 shows the results from the initial simulations. In this study, the resulting maximum stress were analyzed to evaluate the effect of adding a septa and longitudinal stiffeners to a hollow tube design. It can be seen that when compared to a hollow tube of the same thickness, the addition of the septa increases the maximum stress in the spine, meaning it reaches its ultimate tensile stress (UTS) at a lower force. The addition of the longitudinal stiffeners on their own also increases the maximum stress in the spine, but unlike the smooth line of the septa, the results oscillate erratically. However, fig.4 does show that when combined the longitudinal stiffeners and septa collectively decrease the maximum stress in the spine, and increase the force required for the spine to reach its UTS from 62 kN to 92 kN.

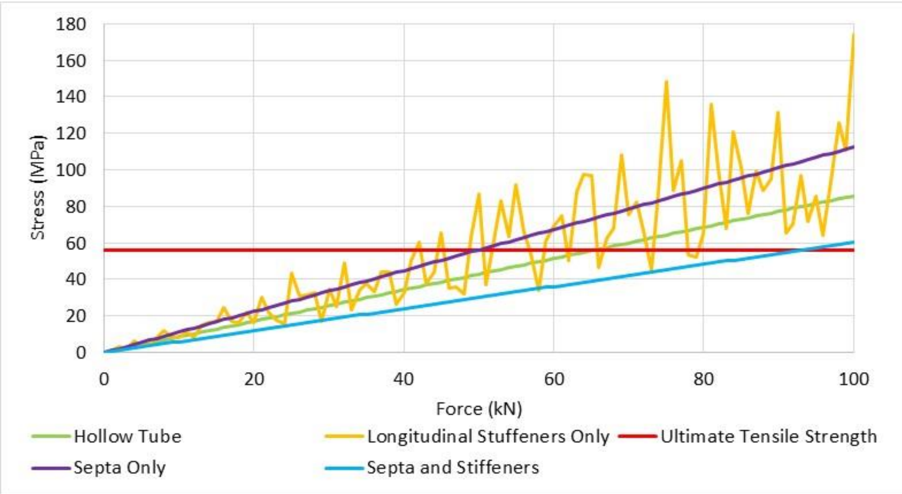

Fig. 4. Resulting stress profiles

4.2 Full Factorial Analysis

A full factorial design of experiment (DOE) was conducted (Table 4) to determine the optimum design parameters. Also, a Pareto analysis (Fig.5) was conducted to determine the effect that each design factor has on the resulting maximum stress. The analysis concludes that factors B (number of stiffeners) and C (stiffener thickness) have the highest influence over the maximum stress.

The normal probability plot shown in Fig. 6 verified the distribution of the data used in the experiments. The results fit the line well suggesting the data is reliable and error free. Fig. 7 gives the main effects plot for stress, with the optimum factors given in Table 5. A confirmation run was carried out to ensure the results were correct. The model was then subjected to increasing forces, so that the force at failure could be determined. The results are displayed in Fig. 8, and it can be seen that the spine reached its UTS at approximately 1250 kN.

Table 4. FACTORS USED FOR FULL FACTORIAL ANALYSIS

Run	Factor				Maximum Stress (MPa)
	A	B	C	D	
1	-1	-1	-1	-1	55.16
2	1	-1	-1	-1	36.08
3	-1	1	-1	-1	30.65
4	1	1	-1	-1	26.69
5	-1	-1	1	-1	30.50

6	1	-1	1	-1	28.25
7	-1	1	1	-1	20.84
8	1	1	1	-1	19.22
9	-1	-1	-1	1	39.88
10	1	-1	-1	1	40.24
11	-1	1	-1	1	32.13
12	1	1	-1	1	25.26
13	-1	-1	1	1	30.50
14	1	-1	1	1	28.25
15	-1	1	1	1	20.84
16	1	1	1	1	19.22

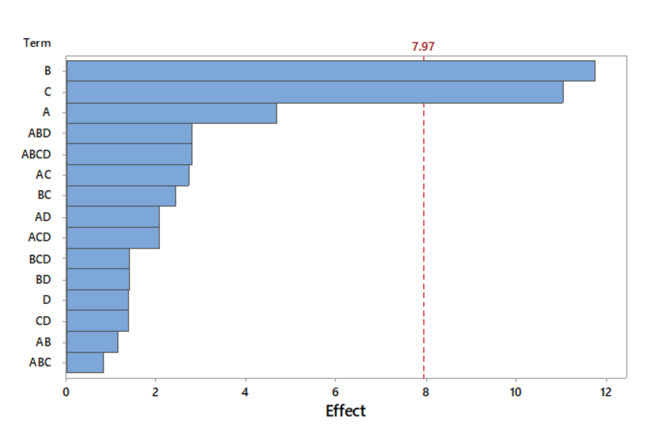

Fig. 5. Pareto Chart of the Effects

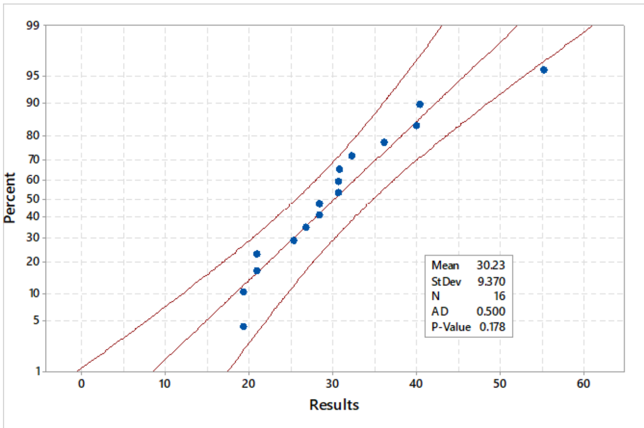

Fig. 6. Normal Probability Plot

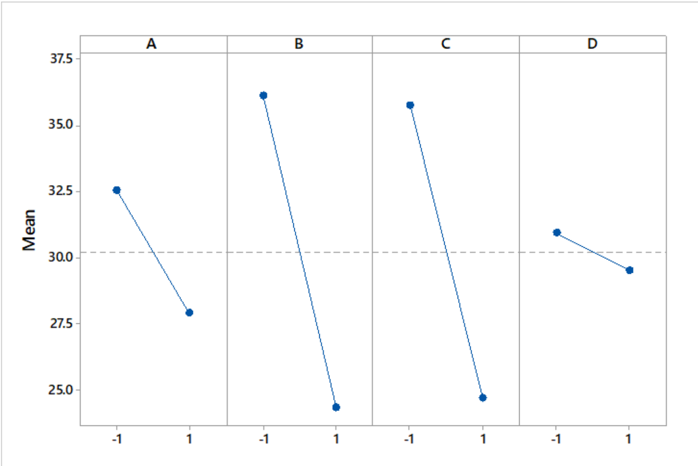

Fig. 7. Main Effects Plot for Stress

Table 5. Optimum Factor Levels

Factor	Level	Value
A. Wall Thickness (mm)	-1	6.5
B. Number of Stiffeners	-1	20
C. Stiffener Thickness (mm)	-1	25
D. Septum Spacing (mm)	1	60

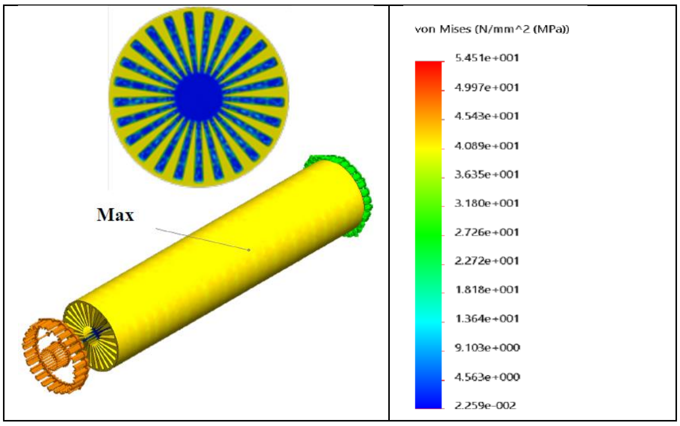

Fig. 8. Stress distribution in the models at maximum force

5 COMPARISON TO STEEL

To gain an understanding of the benefits that producing bio-inspired components through digital manufacturing can provide, the resulting mechanical properties were compared against alternative materials. In particular, the PLA hedge spines developed within this research were compared against tubular steel sections in 201 stainless steel, AISI 1010 & AISI 1018. Table 6 displays the material properties. It can be concluded the results from the PLA samples are comparable to that obtain from metal with regards to maximum compressive force and strength-to-weight-ratio. This demonstrates the potential to use the design of the hedgehog spines for applications such as crash structures.

Table 1. STEEL TUBING PROPERTIES

	201 Stainless Steel [8]	AISI 1010 Cold Drawn [9]	AISI 1018 Cold Drawn [10]	PLA Hedgehog spine
Volume (m3)	0.009	0.009	0.009	0.0502
Density (kg/m3)	6800	7870	7870	1240
Max Compressive Force (kN)	1150	1500	1860	1250
Strength-to-Weight Ratio	1918	2161	2680	2200

6 CONCLUSION

The aim of this paper was to demonstrate the benefits that digital and additive manufacture provide Designers with regards to delivering more sustainable and environmentally friendly manufacturing platforms. In particular, this study analyzed the benefits that mimicking hedgehog spines delivers. This was achieved through computational modelling of an individual spine and optimizing through a DOE Full Factorial study.

The main findings from this paper were:

- The initial testing showed that the strength provided by the unique internal structure of the spine comes from a combination of longitudinal stiffeners and equally spaced septa. However, separately these components act as stress raisers.
- The DOE analysis further proved that cross-sectional area was the governing factor of stress in the spine. In particular, the thickness of the longitudinal stiffeners had the greatest effect on the stress, closely followed by the number of stiffeners.

• The research in this paper is a starting point for the creation of a knowledge repository with focus on the applicability of bioinspired structures to aid design functionality and deliver more sustainable products due to optimized material usage.

7 FUTURE WORK

The main conclusions from this work offer the potential to broaden the knowledge base of both the application of bio-inspired components and how inherent variation within digital manufacturing platforms will affect the resulting mechanical properties. Additional future work can also investigate the validation of the simulation results through different methods of digital manufacturing platforms.

References

[1] Julian F.V Vincent, Olga A Bogatyreva, Nikolaj R Bogatyrev, Adrian Bowyer, Anja-Karina Pahl. Biomimetics: its practice and theory. 2006 August 22.
[2] Izumi H, Suzuki M, Aoyangi S, Kanzaki T. Sensors and Actuators A: Physical. January 2011. Volume 165, Issue 1. Pages 115-123.
[3] Kesong Liu, Lei Jiang. Nano Today. 2011 April. Volume 6, Issue 2. Pages 155-175.
[4] Nathan B. Swift, Bor-Kai Hsiung, Emily B. Kennnedy, Kwek-Tze Tan. Dynamic impact testing of hedgehog spines using a dual-arm crash pendulum. Journal of the Mechanical Behavior of Biomedical Materials. 2016 August. Volume 61. Pages 271-282.
[5] J.F.V. Vincent. Survival of the cheapest. Materials Today. 2002 December. Volume 5, Issue 12. Pages 28-41. Available from: http://www.sciencedirect.com/science/article/pii/S1369702102012373
[6] Emily B. Kennedy, Bor-Kai Hsiung, Nathan B. Swift, Kwek-Tze Tan. Static flexural properties of hedgehog spines conditioned in coupled temperature and relative humidity environments. Journal of the Mechanical Behaviour of Biomedical Materials. 2017 November. Volume 75. Pages 413-422.
[7] J. F. V. Vincent, P. Owers. Mechanical design of hedgehog spines and porcupine quills. Journey of Zoology. 1986 September. Volume 210, Issue 1.
[8] Navpad Steel. 201 Stainless Steel Tube [Internet]. 2017. [Cited 2018 April 29]. Available from:http://www.navpadsteel.com/201-stainless-steel-seamless-welded-tubes-supplier.html
[9] AZO Materials. AISI 1010 Carbon Steel (UNS G10100) [Internet]. 2012 September 21. [Cited 2018 April 29]. Available from: https://www.azom.com/article.aspx?ArticleID=6539
[10] Matweb. AISI 1018 Steel, cold drawn [Internet]. 2018. [Cited 2018 April 29]. Available from:http://www.matweb.com/search/datasheet_print.aspx?matguid=3a9cc570fbb24d119f08db22a53e2421