UNIVERSITY OF WOLVERHAMPTON

Additive manufacturing of stiffness optimised auxetic CoCrMo meta-biomaterial bone scaffolds

Dr Chameekara Tharumal Wanniarachchi

Bone reconstruction using scaffolds

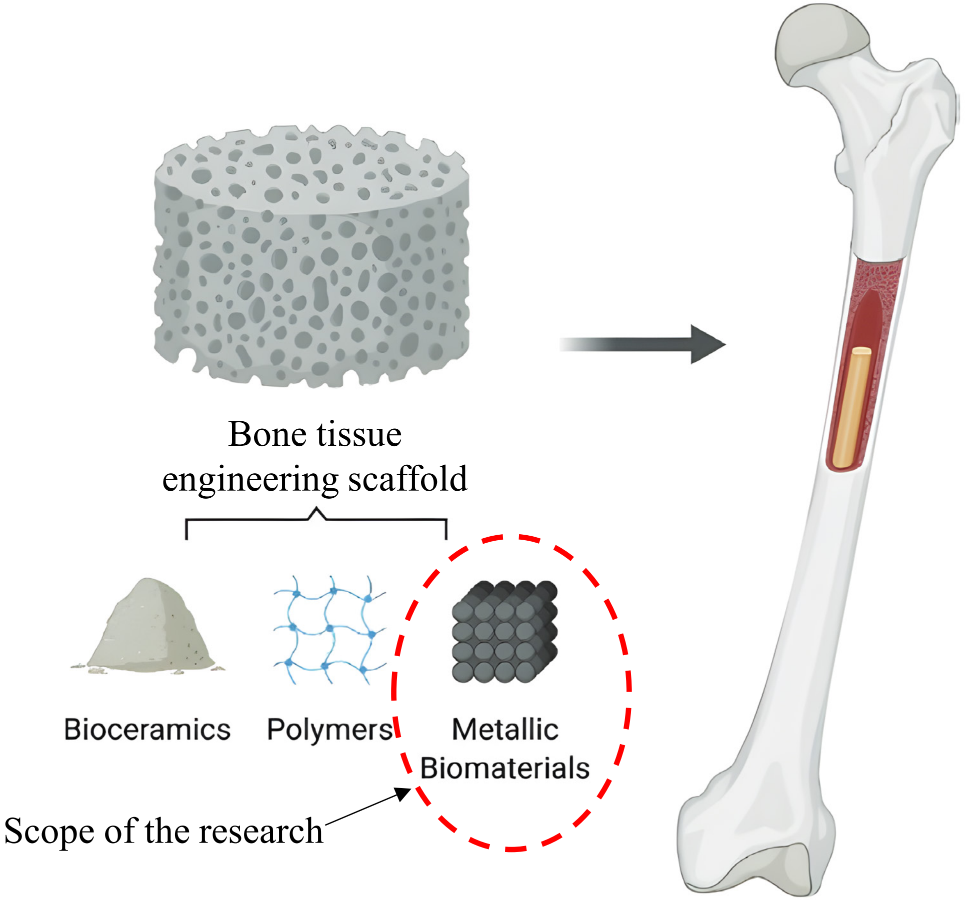


Fig. 1. Bone scaffold reconstruction process

- Bone scaffold is a porous structure that acts as a template for bone tissue formation during the healing of segmental bone defect.
- It uses artificial scaffolds as shown in Fig. 1 and the digital manufacturing techniques such as additive manufacturing offer significant potential for engineering bone scaffolds featuring complex porous architecture leading to auxetic behaviour.
- Although bio ceramics, polymers and metallic biomaterials are commonly used to make bone-tissue scaffolds, their mechanical strengths are inadequate to withstand a high loading.
- Scaffold characteristics
  - Porosity
  - Biocompatibility
  - Mechanical properties

Challenges in load-bearing bone scaffolds

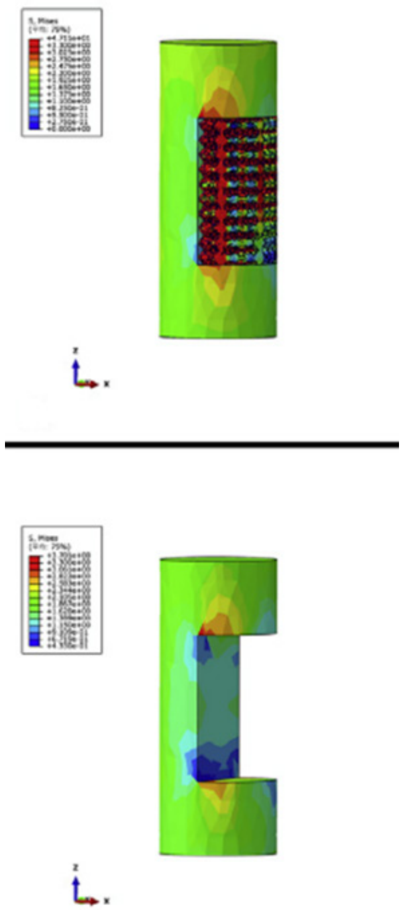


Fig. 2. The stress shielding result of FE simulation (a) with scaffold (b) without scaffold

- Bone has a basic stress-strain relationship as do all structural materials, but because bone is a living organ its strength varies with age, sex, location, orientation of the load, and test condition.
- Repair and restoration of damaged bone is a major clinical challenge.
- One of the major challenges in orthopedics is to develop implants that overcome current postoperative problems such as osteointegration, proper load bearing, and stress shielding.
- The mismatch of elastic modulus between scaffold implants and bone tissues is critical in managing stress shielding.
- The current implants and scaffolds clinically used do not provide stiffness matching leading to nonhomogeneous stress transmission between the implants and surrounding bone tissue.

What are auxetic materials?

- Auxetic structures are peculiar structures that as they expanded and decreased when compact, have the potential to increase the scale as shown in Fig. 3.

- In comparison, instead of the more traditional materials, the auxetic materials exhibit detrimental Poisson's ratios in various directions.

- Poisson's ratio $(\upsilon) = - \frac{axial\ strain}{longitudanal\ strain}$

- Auxetic structures display distinct deformation and functional properties owing to the negative Poisson's ratio.

- Due to its unusual formation, auxetic frameworks are more essential than the other structural elements in biomedical applications.

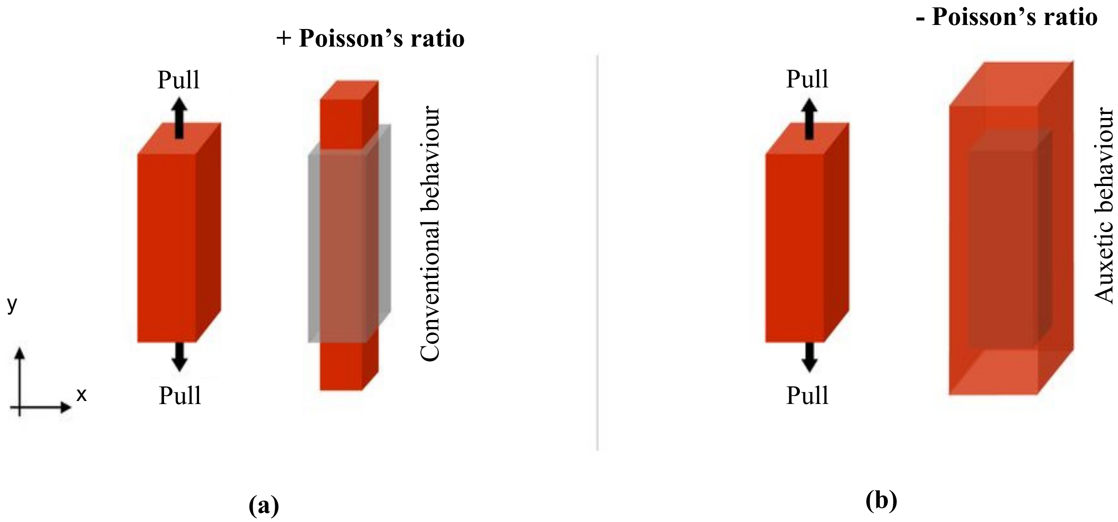


Fig. 3. Deformation of materials showing (a) behaviour of a conventional material resulting in positive Poisson's ratio and (b) showing auxetic materials resulting in negative Poisson's ratio.

UNIVERSITY OF WOLVERHAMPTON

Significance of auxetic materials in bone scaffolds

- A number of biological tissues have been reported as behaving in an auxetic manner, defined by a negative Poisson's ratio (skin, bone, artery, tendon)

- If the target tissue is auxetic, an auxetic scaffold would most closely match the properties of this tissue. The matching of this characteristic would be beneficial in recreating the loading environment that cells would naturally experience.

- In addition to a lightweight structure and morphing properties, which makes auxetic geometry ideal for interacting with the human body.

- The gradient distribution of three-dimensional re-entrant auxetic cells may be a potential solution for reducing micromotion and reduce stress shielding effects that can lead to bone resorption.

- Due to its lateral contraction behaviour under loading, auxetic structures could potentially reduce the stress on the surrounding tissues during tampon extraction.

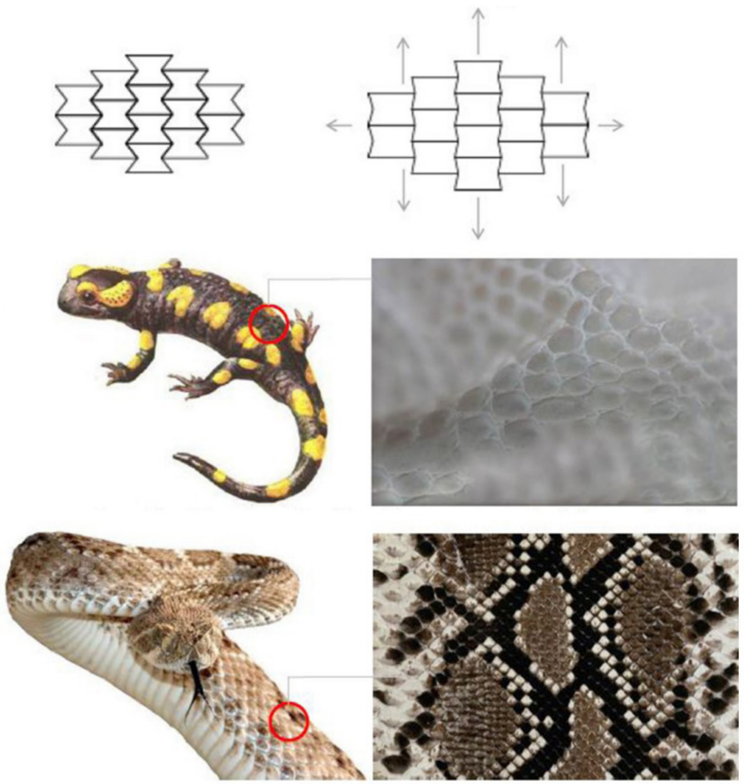
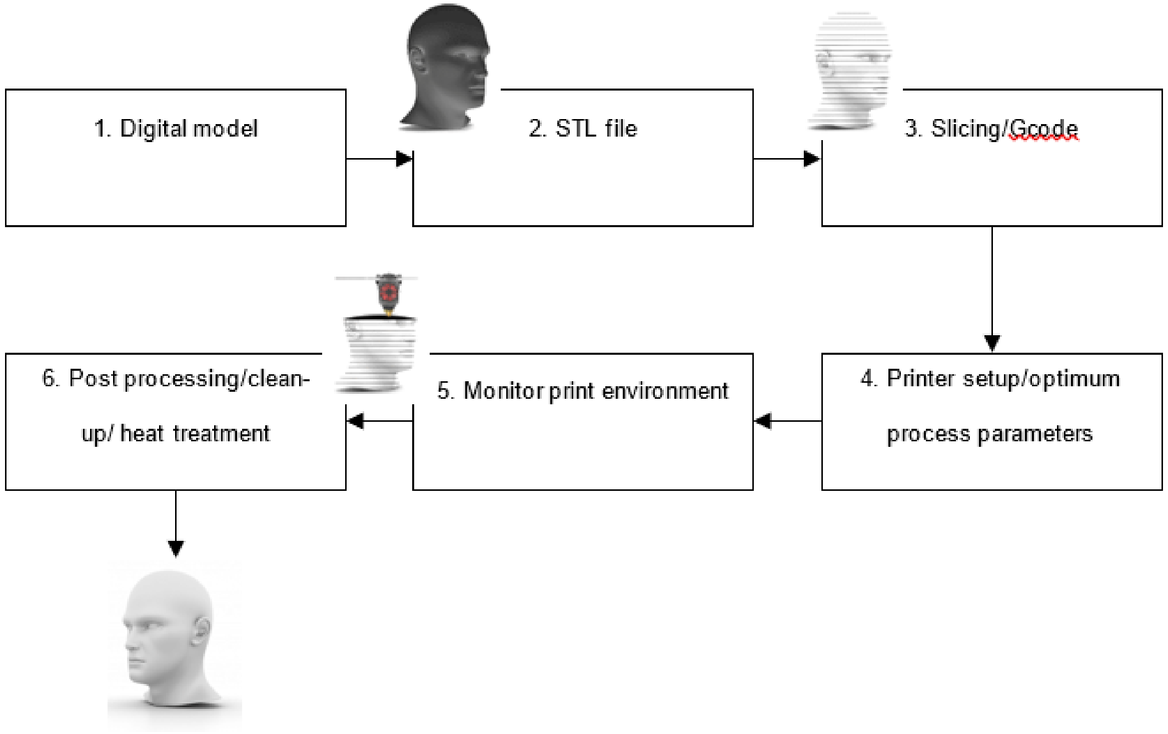


Fig. 4. Reference to the auxetic structure to the skins of salamanders and snakes

UNIVERSITY OF WOLVERHAMPTON

Additive manufacturing

Additive manufacturing (AM) can be defined as the procedure of binding materials together to create items from 3D model data, typically layer by layer, unlike subtractive production processes like ordinary machining.



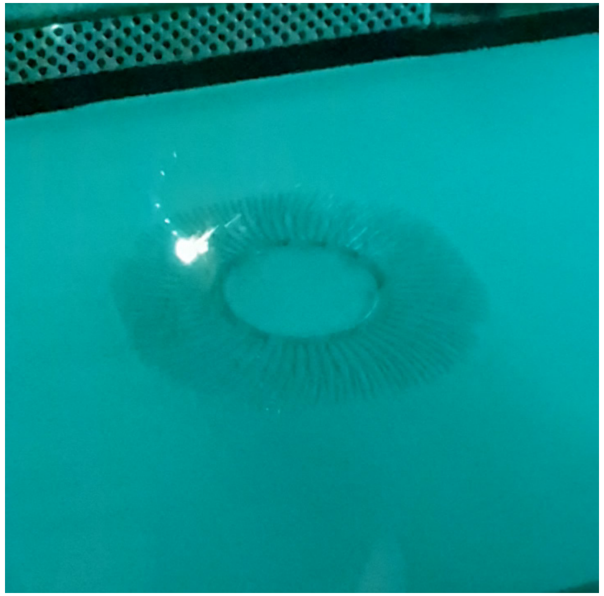


Fig. 5. Steps leading to additive manufacturing from digital model to the final part

Design and manufacturing of selective laser melted samples

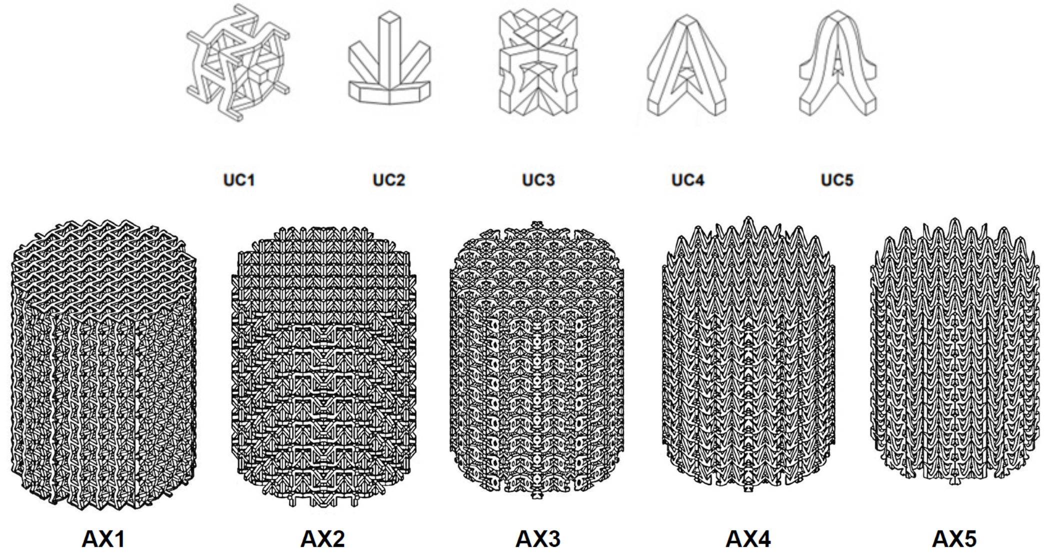


Fig. 6. Scaffold designs featuring auxetic unit cells UC1 to UC5

- In many clinical studies, a critical size of bone segmental defect falls between 1-3 cm resulting in more than 50% of equivalent circumferential length, where the bone cannot heal unsupported.

- The diameter of an equivalent circle that can fit the tibial cross-section dictated the scaffold's radius of 7.25 mm and the height of all the scaffolds developed in this study has 18 mm, qualifying as critical length scaffolds.

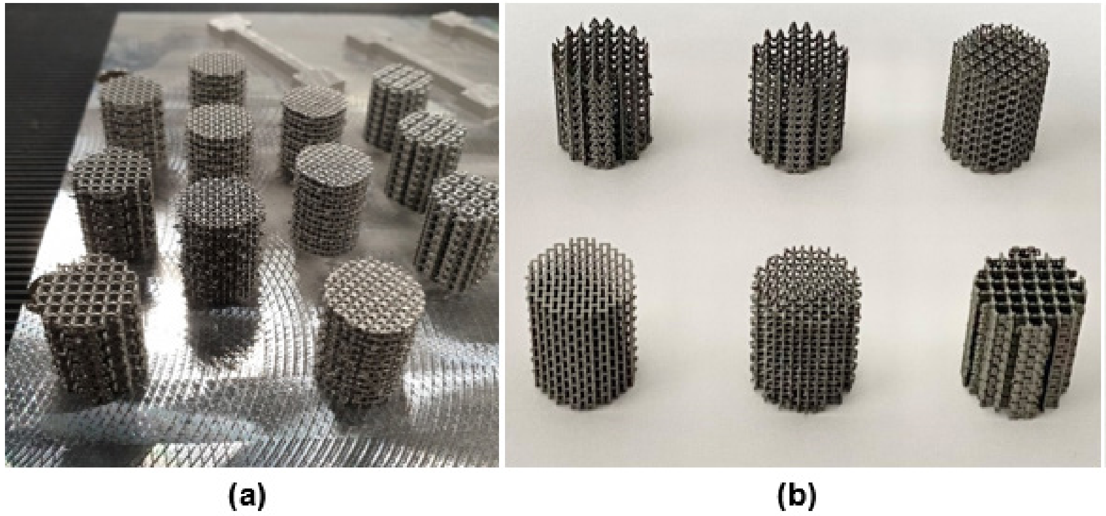


Fig. 7. Selective laser melted CoCrMo samples showing (a) printed samples on the base plate before post-processing, (b) post-processed scaffold samples

Properties	Additively manufactured scaffolds				
	AX1	AX2	AX3	AX4	AX5
Mass (m_{Ax}) grams	6.4	5.7	5.4	4.4	4.6
Relative density (ρ_r)	0.2695	0.2328	0.2183	0.1802	0.1884
Porosity (%)	73.05	76.72	78.17	81.98	81.16

Table 1. Physical parameters and porosity of the additively manufactured scaffolds

Mechanical testing and Finite element modelling

Fig. 8. Mechanical test setup showing compression test for mechanical properties of the auxetic scaffold

Finite element modelling

- After examining numerous element types, the 10 node higher order tetrahedral element (SOLID187) combined with a Bilinear isotropic strain hardening (BISO) material model was used for the analysis.

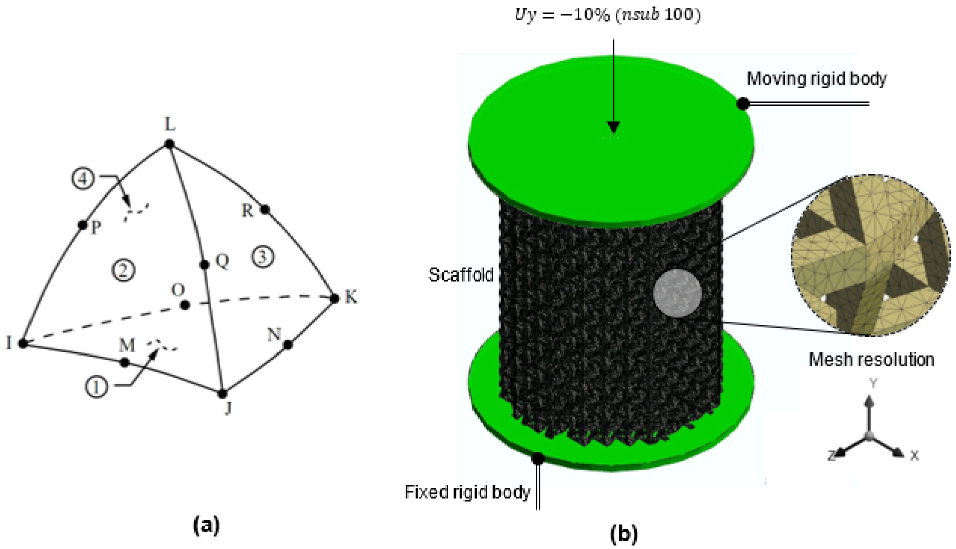


Fig. 9. Finite element model showing the (a) element type and (b) boundary conditions

Mechanical and FEA test results

Design	Manufactured sample porosity (%)	Mean elastic modulus (GPa)	Mean 0.2% Yield strength (MPa)	Mean Ultimate stress σ_{ult} (MPa)	Poisson's ratio
AX1	73.05	1.66±0.47	56±1.24	158±6.65	-0.24
AX2	76.72	1.13±0.02	32±0.81	88.87±3.49	-0.13
AX3	78.17	1.57±0.02	36±0.62	104.53±2.40	-0.1
AX4	81.98	1.27±0.03	52±4.71	51.66±4.14	-0.16
AX5	81.16	1.6±0.08	40±0.84	97.9±3.83	-0.16

Table 2. Experimental mechanical properties of scaffolds

- Overall, the elastic modulus of the structures is varying in between 1.13 GPa and 1.66 GPa, and the yield strength is between 32MPa and 56MPa, with AX2 showing the lowest performance.
- Compressive test results showed that there is no significant trend between elastic modulus and the yield strength among auxetic materials

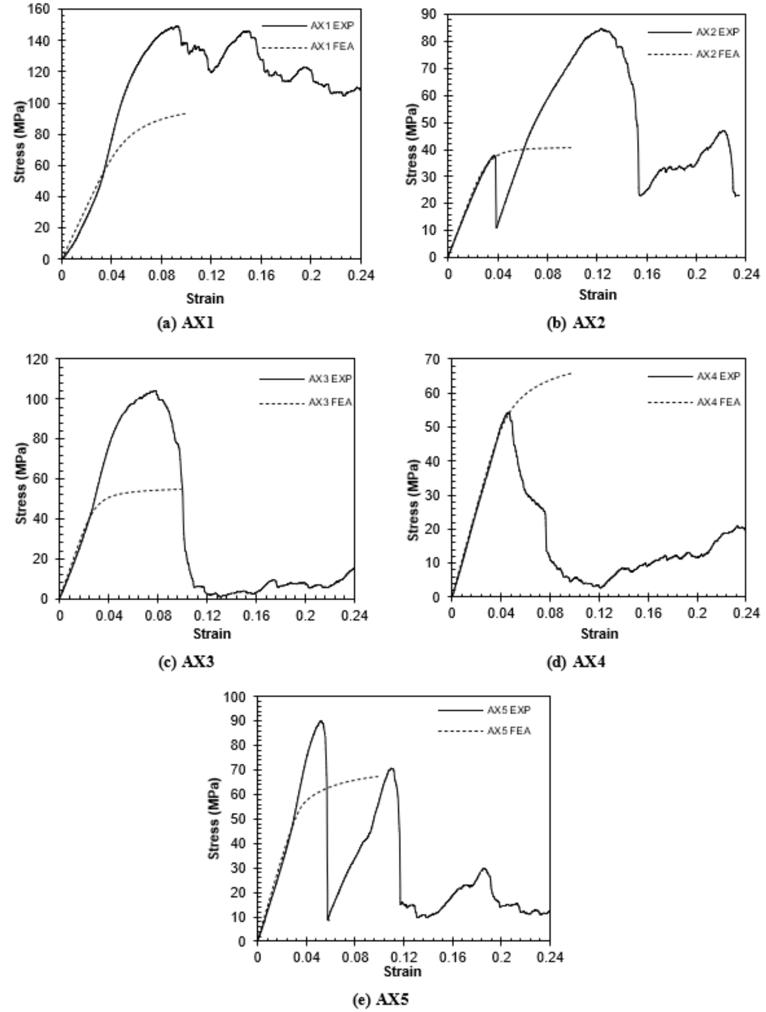


Fig. 10. Comparison of stress-strain curves obtained from the finite element model and physical tests for (a) AX1, (b) AX2, (c) AX3, (d)AX4 and (e) AX5

Validation of FEA and experimental calculations

Scaffold	AX1	AX2	AX3	AX4	AX5
E FEA (GPa)	1.68	1.17	1.59	1.30	1.65
E EXP (GPa)	1.66	1.13	1.57	1.27	1.60
E % Difference	1.19	3.41	1.25	2.30	3.03
σ_y FEA (MPa)	54	31	35	50	39
σ_y EXP (MPa)	56	32	36	52	40
σ_y % Difference	3.57	3.12	2.77	3.84	2.50
υ FEA	-0.26	-0.17	-0.12	-0.19	-0.20
υ EXP	-0.24	-0.13	-0.10	-0.16	-0.16
υ % Difference	2.12	4.10	2.14	2.51	3.60

Table 3. Comparison between the finite element predicted and actual test data on parameters of interest where E refers to the elastic modulus, σ_y yield strength and υ the Poisson's ratio

- The difference between the numerical and experimental data can be primarily attributed to the influence of the SLM additive manufacturing technique.
- It can be seen (Fig. 11) that the trend in stress concentration is consistent with the yield strength observed, signifying a reduction in strength due to stress concentration.

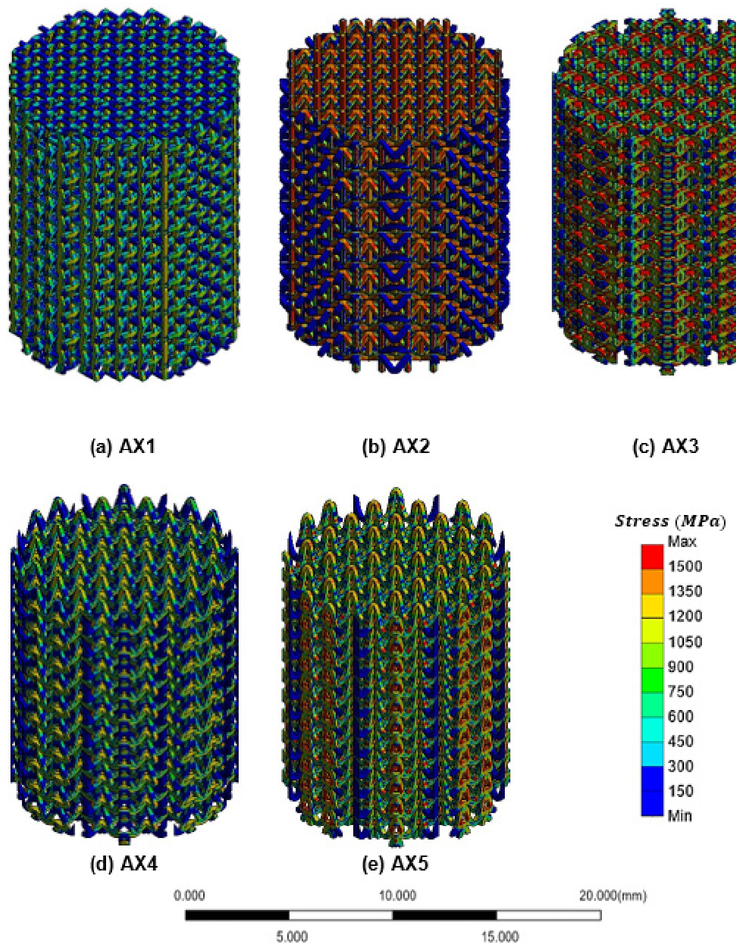
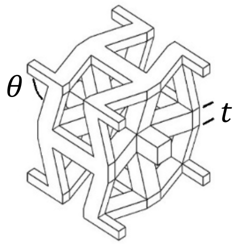


Fig. 11. Comparison of stress-strain curves obtained from the finite element model and physical tests for (a) AX1, (b) AX2, (c) AX3, (d)AX4 and (e) AX5

Parametric analysis

Parametric analysis of best auxetic design :Response surface methodology - the strut thickness (t) and auxetic angle (θ) were chosen as the variables to investigate their significance on both the auxetic behaviour and mechanical performance of the scaffold



Variable	$\boldsymbol{\theta(deg.)}$	$\boldsymbol{t(mm)}$
-1	65	0.25
0	70	0.30
1	75	0.35

Table 4. Design variables selected for the auxetic scaffold to be optimised under Scenario 2

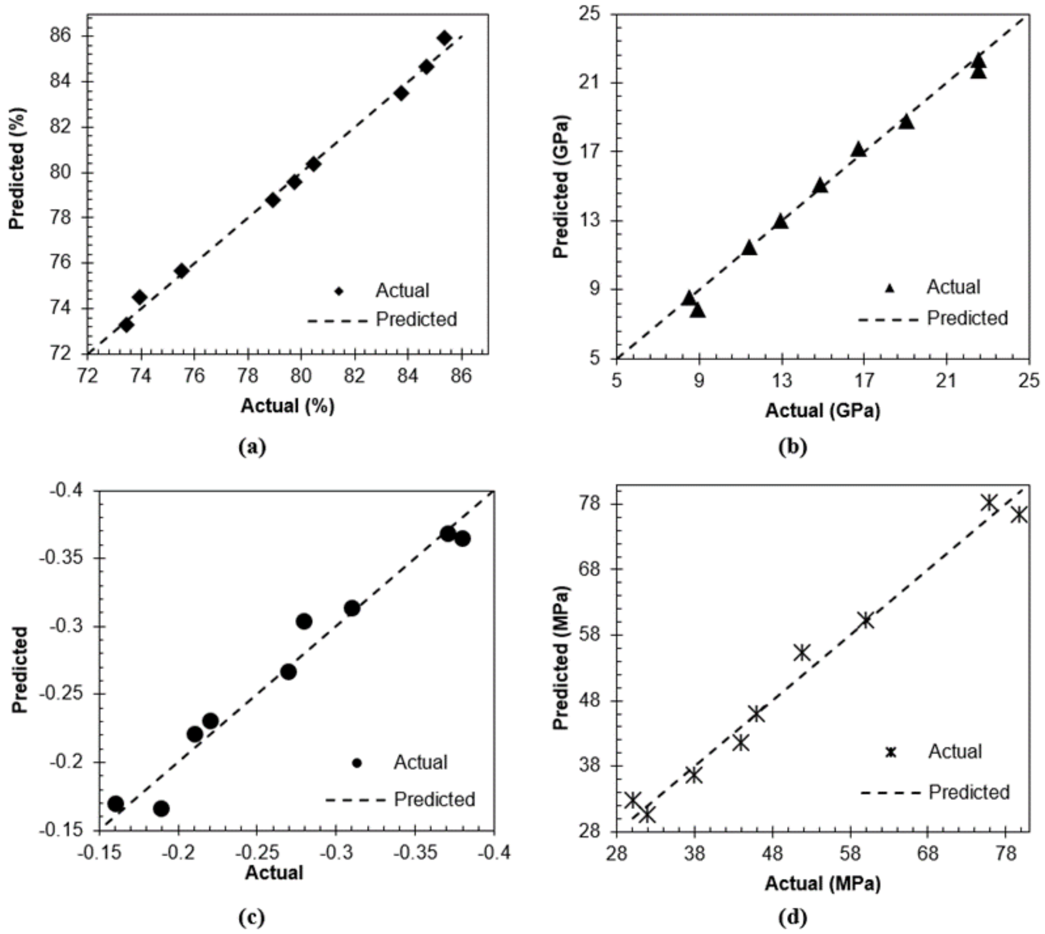


Fig. 12. Comparison between RS model and finite element predictions for AX1 showing (a) Porosity (φ) (b) elastic modulus (E), negative Poisson's ratio $(-\upsilon)$ and yield strength (σ_y)

UNIVERSITY OF WOLVERHAMPTON

Optimisation & validation of the best auxetic design

UNIVERSITY OF WOLVERHAMPTON

- Multi-objective optimisation methodology

Multi-objective optimisation methodology can be adopted when a solution to satisfy multiple objective functions are required.

The general formulation of the optimisation problem can be represented by using Eqn.

$$\begin{cases} Minimise\ f(x) = [f_1(x), f_2(x), \ldots\ldots, f_i(x)] \\ s.t \qquad x^l \leq x \leq x^u \end{cases}$$

where, $x = (x_1, x_2, \ldots, x_k)$ is the vector of k design variables, x^l and x^u are the lower and upper limits of the design variables, respectively, and $f(x)$ is the objective function.

Parametric analysis of the scaffolds in previous slide showed the dependence of design variables on the responses $(\varphi, -\upsilon, E\ and\ \sigma_y)$

Personalisation parameters	Expectation	Explanation
Negative Poisson's ratio $(-\upsilon)$	Maximise	Highest elastic strain
Elastic modulus (E)	18 GPa	Targeted stiffness matching
Yield strength (σ_y)	Maximise	High strength
Porosity (φ)	Maximise	High porosity

Table 5. Summarising optimisation criteria used for the designs to generate optimum auxetic bone scaffold

Optimisation & validation

- Optimum auxetic bone scaffold

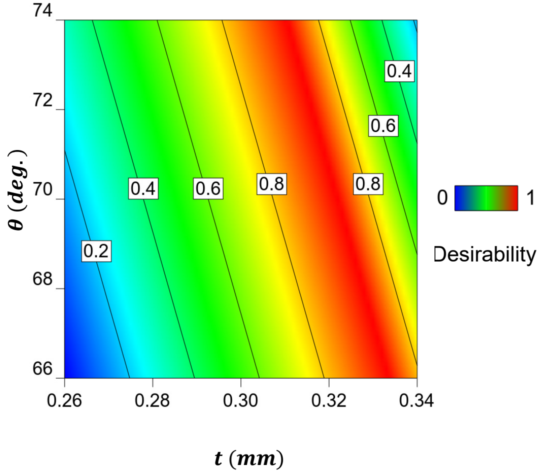


Fig. 13. The desirability of the optimum solution against design variables for AX1

Number	$t\ (mm)$	$\theta\ (Deg.)$	Desirability
1	0.325	67.93	1

Table 6. Predicted optimal solution for AX1

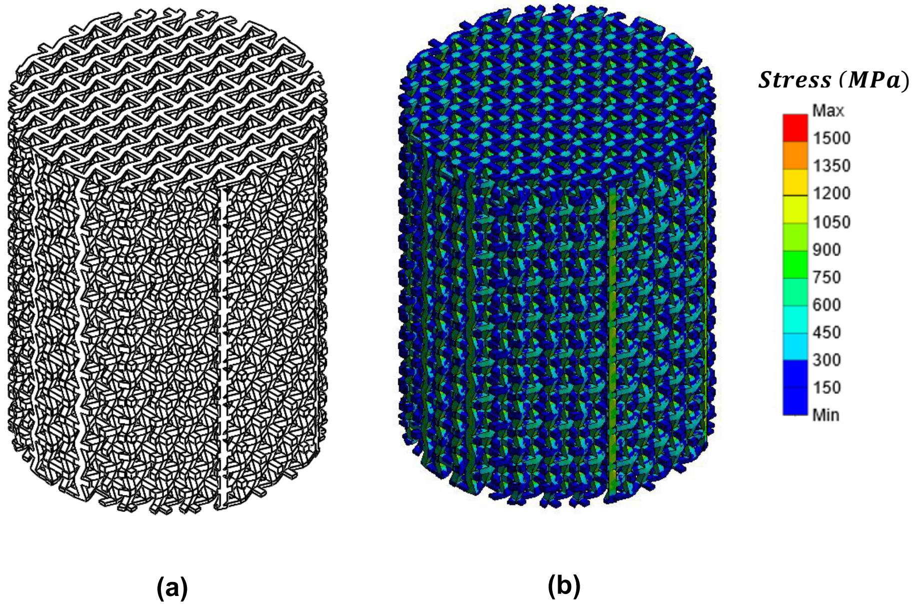


Fig. 14. Optimised AX1 scaffold showing (a) optimum design generated and (b) finite element informed von-mises stress distribution

Item	υ	φ	E	σ_y
Predicted	-0.230	76.042	18	58.59
FEM	-0.223	76.351	17.53	57.2
% Difference	3.04	0.40	2.61	2.37

Table 7. Comparison between predicted and FEM values of the optimum AX1 scaffold design

Thank you