173 Mechanical Behaviour of Additively Manufactured Gradient Scaffold Materials

M. Stagno Navarra[1a], C. Faurat-Narkisian[2], M. Browne[1] and A.R. Hamilton[2b]

[1] Bioengineering Science Research Group, University of Southampton, Southampton SO17 1BJ, UK
[2]Engineering Materials Research Group, University of Southampton, Southampton SO17 1BJ, UK

[a] msn1g16@soton.ac.uk, [b] a.r.hamilton@soton.ac.uk

Abstract. Scaffold materials are used in tissue engineering and regenerative medicine to restore the form and function of damaged tissue by providing a suitable microenvironment for biological cells and tissue. Gradients in scaffold pore structure are enabled by additive manufacturing (AM), and can help elicit desirable biological responses. The mechanical behaviour of porous scaffold materials is important for restoring mechanical functionality of tissue, and can also have an influence on biological response. In this study, the mechanical behaviour of gradient scaffold materials is characterised in quasi-static compression, and compared with uniform scaffolds as functions of porosity and microstructural geometry.

Introduction. Regenerative medicine makes use of engineered tissue scaffold materials to replace and repair damaged tissue. These scaffold materials must satisfy diverse requirements in order to provide a suitable physical, mechanical, and chemical microenvironment to support cells and elicit the desired biological behaviour. In the case of musculoskeletal tissue — such as bone, cartilage, or the osteochondral bone-cartilage interface — it is desirable for tissue scaffolds that biodegrade at the rate of new tissue formation, with high porosity and connectivity for cell attachment and nutrient transport, and with mechanical strength and stiffness matching the surrounding tissue [1]. However, satisfying these interdependent requirements simultaneously is an outstanding challenge. Additive manufacturing (AM) techniques are a powerful tool for potentially overcoming this challenge by enabling the deterministic design of microstructured scaffold materials. AM tissue scaffolds with designed gradients in pore structure have been reported to positively affect cell seeding and attachment, nutrient transport, and to encourage cell differentiation and expression [2]. In this work, the mechanical response and properties of such scaffolds are investigated.

Materials and Methods. Fused filament scaffold materials were additively manufactured using a Prusa i3 Mk3 fused filament fabrication (FFF) 3D printer with 0.4 mm diameter extrusion nozzle. Non-medical grade poly(lactic acid) (PLA) with density of 1.24 g/cm3, tensile modulus 3.31 GPa, and tensile strength 110 MPa (as specified by the manufacturer) was sourced from 3DFilaPrint®, UK.

The porous microstructure of scaffolds consisted of unit volume elements of aligned and offset fused filaments (Figure 1). Unit volume elements were assembled into cubic scaffold specimens with overall dimensions 25 mm^3. All scaffolds had a prescribed filament width (d) of 0.4 mm and a layer height (h) of 0.35 mm. The spacing between fused filaments (g) was selected to span a range of porosities from ~60–95% and was spatially unchanged in uniform scaffold specimens. Discrete gradient scaffolds were produced with an aligned microstructure and filament spacings that changed mid-way through the height, resulting in specimens with discrete regions of different microstructures on the top and bottom halves. More continuous gradient scaffolds were produced with aligned filament spacings that changed every three layers.

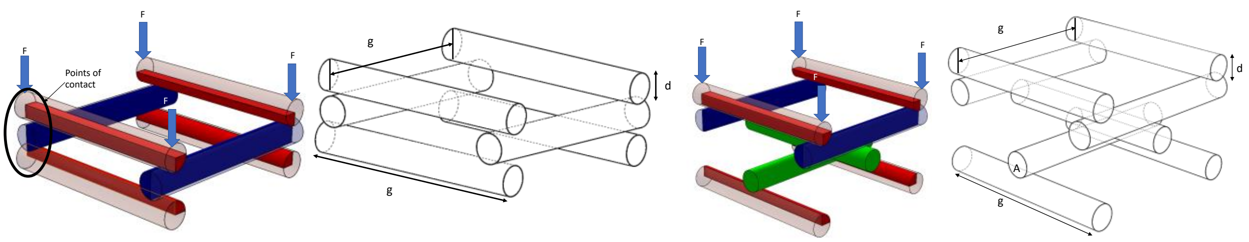

Figure 1. Unit volume elements of aligned (left) and offset (right) fused filament scaffolds.

The mass and overall dimensions of scaffold specimens were measured using an analytical balance (Mettle Analytical Balance, accurate to 0.01 g) and digital callipers (SPI, accurate to 0.01mm), and were used to calculate a measured density. The relative density and porosity were calculated based on the specified density of PLA filament. Quasi-static mechanical compression tests were conducted on an Instron 5569 test machine with a 2 kN load cell at a constant displacement rate of 1 mm/s. The loading direction of the applied force (F) is indicated relative to the microstructure in Figure 1 (vertical). Nominal stress and strain were calculated from load and crosshead displacement measurements using the overall specimen dimensions. Optical strain measures were derived from calibrated images captured throughout selected mechanical tests.

Results. The measured porosity of scaffolds ranged from 54–93%. Representative stress-strain curves are shown in Figure 2(a) for uniform aligned, uniform offset, and discrete gradient scaffolds with selected filament spacings (g) and overall porosities. The aligned scaffolds exhibited relatively high elastic moduli in the initial linear elastic region, whereas offset scaffolds exhibited lower elastic moduli at similar spacings and porosities. This difference in linear elastic stress-strain behaviour is consistent with axial compression as the dominant deformation mode in aligned scaffolds, and flexure as the dominant mode in the offset scaffolds. Discrete gradient scaffolds exhibited an elastic modulus consistent with the higher porosity region and an offset microstructure. Although the top and bottom halves of discrete gradient scaffolds were aligned microstructures, the interface between these two segments was offset due to the transition in filament spacing, which may explain why the linear elastic region is similar to uniform offset scaffolds.

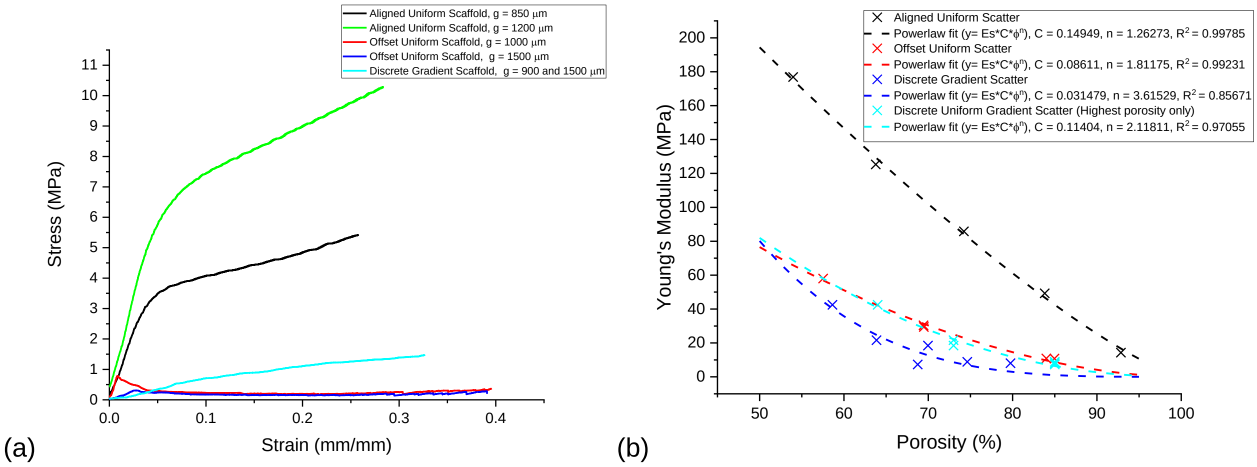

Figure 2.

The elastic modulus of scaffolds was determined as the slope of the stress-strain curves in the initial linear elastic region, and is plotted as a function of porosity in Figure 2(b). The power-law trend predicted by micromechanical models for porous materials fit the uniform scaffold data well, as indicated by the coefficients of determination, R^2, in Figure 2(b). The best-fit power law trend for uniform aligned scaffolds had an exponent close to one (n = 1.26), consistent with axial deformation, while the exponent for uniform offset scaffolds was close to 2 (n = 1.81), consistent with flexure. The elastic modulus of discrete gradient scaffolds overlapped the trend for uniform offset scaffolds very closely when plotted as a function of the highest porosity region. This again indicates that the highest porosity and interface dominated the elastic behaviour of discrete gradient scaffolds.

Conclusion and Future Work. The mechanical behaviour of scaffold materials with gradients in porous microstructure was investigated for potential applications in regenerative medicine. The mechanical behaviour of uniform scaffolds was consistent with axial deformation for aligned scaffolds, and with flexural deformation for offset scaffolds. The elastic modulus of discrete gradient scaffolds was similar to offset scaffolds with porosity of the most porous gradient region; this suggests that mechanical behaviour is dominated by the highest porosity region and the offset microstructure at the interface. Ongoing and future work is further analysing the full stress-strain behaviour and mechanical properties of gradient scaffolds, and is investigating the mechanical behaviour of more continuous gradient scaffolds as well as localised mechanical response in gradient scaffolds using optical strain measurement techniques.

References

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