Imperial College London

Topology Optimisation of Lattice Structure Additive Manufactured Knee Implants

Author: Asad Raja

Supervisor: Jonathan Jeffers

Introduction

With an increased demand for knee implants amongst the ageing population, there have been increased incidences of complication in implant patients. Modern knee implants are made from solid titanium, which has a young's modulus of ~110GPa, far greater than that of the surrounding bone (0.3-5GPa). This causes a stress shielding effect which results in bone weakening and complications. The Biomechanics Group have developed a method of predicting the anisotropic properties of lattice material as well as mapping the bone apparent modulus of a tibia from CT scans [1]. A lattice structure titanium alloy (Ti6Al4V) tibial tray knee implant component is therefore being developed, with regional modulus targets defined such that values are matched to that of the surrounding bone, to improve bone remodelling and prevent complications. However, this design will yield under the 900 N load of the ISO14879 fatigue strength certification test (Figure 1).

Aim

To adapt the design of the lattice structure tibial tray to improve yielding behaviour when exposed to a static ISO test load, whilst maintaining the favourable bone remodelling properties.

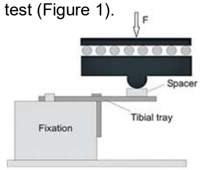

Figure 1: ISO14879 Test Schematic

Topology Optimisation

Topology optimisation is a developing field of mathematical design simulation that seeks to create a geometry within a design space which maximises or minimises a certain mechanical property subject to another mechanical property constraint. The process works by assigning pseudo-volume fraction design variables to each element of a finite element mesh and optimising the values. The most common example is the application of the Solid Isotropic Material Penalisation (SIMP) approach to the binary compliance problem. This maximises the structure's stiffness subject to a mass reduction constraint (Figure 2). The penalisation imparts binary volume fractions, creating a structure made entirely of solid material or voids. A non-penalising approach would be needed for topology optimisation applications to a lattice structure, to ensure volume fraction of all elements have intermediate values.

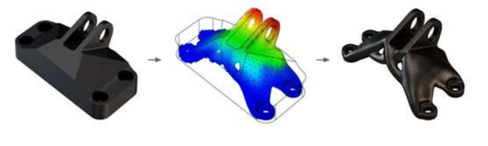

Figure 2: SIMP binary compliance topology optimisation example

Methodology

A simulation environment was created in MATLAB by applying a mesh creation and boundary condition application scheme using CAD model inputs. Finite element theory was then used to assemble a global stiffness and a global von mises stress matrix. By implementing a SIMP binary compliance topology optimisation algorithm, the simulation environment was validated by reproducing a standard result for an end-loaded cantilever beam. Comparison of the simulation's wall stress and end-deflection values for the beam with hand calculations gave acceptable errors, further validating the simulation.

Three methods were investigates for optimising the tibial tray design. Adjusted designs were compared to the original modulus-matched *'Control'* design.

1. A non-SIMP stiffness-maximising topology optimisation:

The standard topology optimisation was minimally adjusted. Without penalisation, the stiffness of the structure was maximised subject to constraints upon regional average volume fractions corresponding to regional modulus targets for effective bone remodelling. The *'Stiffness Top Op'* design was obtained.

2. A looped stress limiting approach:

The yielding behaviour of the structure was improved using the process in Figure 3 – each element's yield stress was matched to its experienced stress to define a stress limited design using an empirical yield stress-volume fraction relation, and elements predicted to fail were adjusted to these values in a hybrid design. This was highly sensitive to the initial condition design and the number of iterations. Four designs were obtained:

	Initial Condition Design	**Number of Iterations**
'Stress Limited'	*'Stiffness Top Op'*	Half*
'Stress Limited Control'	*'Control'*	Single
'Stress Limited Top Op'	*'Stiffness Top Op'*	Single
'Convergent Stress Limited'	All element volume fractions set to average of regional targets for modulus-matching.	Until Convergence

3. A non-SIMP stress-constrained topology optimisation:

The deviation of volume fractions from their modulus target-corresponding values would be minimised with a constraint on stress. A highly novel and comprehensive approach to achieving the project aim, which required the derivation of the non-penalised P-norm stress sensitivity. A complex analytical solution was developed. Future work should validate this.

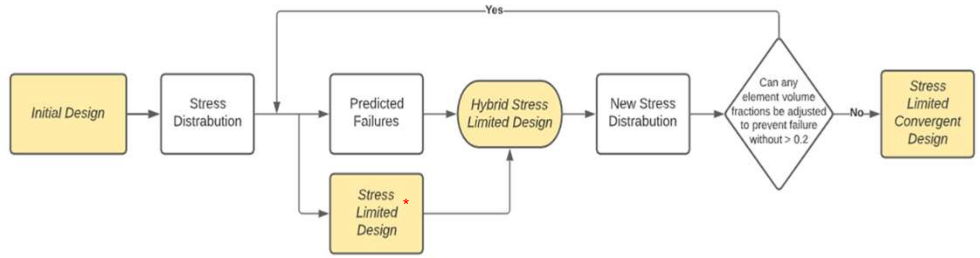

Figure 3: Looped stress limiting approach

Results and Discussion

The results showed that all designs improved yielding behaviour compared to the *'Control'* design, with a fall in the percentage of elements predicted to fail. The *'Stiffness Top Op'* design showed the smallest reduction at 33.5%. The first three stress designs obtained from the stress limiting process reduced this further to 20-30%, and the *'Convergent Stress Limited'* design reduced this further still to 12.0% (Figure 4). Deflection values at significant tibial tray positions also fell in this general order. The average deviation from the modulus targets for ideal bone regeneration was more sporadic between designs. The *'Stress Limited Control'* design (Figure 5) proved to be the best compromise, with 22.2% of elements predicted to fail – a 44.9% improvement upon *'Control'* – and a 12.0% average modulus target deviation. If the volume fraction was to be kept constant through the structure, a minimum 0.17 value would be needed for no element failures to be predicted, which represents a 112.5% average deviation from modulus targets. The sensitivity of the stress limited approach to the initial condition design and iteration number offered scope for further exploration.

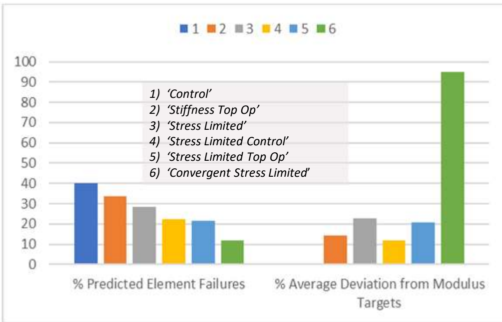

Figure 4: Element failure and modulus target deviation comparison

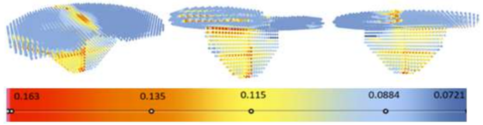

Figure 5: Volume fraction distribution of 'Stress Limited Control'

Conclusion

A tibial tray design with ideal bone remodelling capability was adjusted to improve yielding behaviour under a static ISO test-defined 900 N load. Though the non-SIMP stiffness maximising topology optimisation improved the yielding behaviour to an extent with a modest compromise on remodelling behaviour, the stress limiting process addressed the yielding behaviour more directly and effectively. The '*Stress Limited Control'* design improved yielding behaviour by 44.9% with the lowest compromise upon remodelling out of the results obtained (12.0% deviation from modulus targets). The designs have been additive manufactured (Figure 6) for lab testing.

Figure 6: Additive manufactured 'Stress Limited Control'

References

[1]: Munford MJ, Ng KCG, Jeffers JRT. Mapping the Multi-Directional Mechanical Properties of Bone in the Proximal Tibia. Advanced Functional Materials. 2020.