Finite element analysis & topology optimization of biodegradable magnesium-alloy intramedullary rods

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Introduction

Intramedullary rods (IRs) are a common surgical fixation method for long bone fractures. Bone remodeling requires loading to develop appropriate bone density. Conventional IRs made from stainless steel or titanium alloys can cause stress shielding in the bone due to the significantly higher stiffness of the implant compared to bone. Magnesium alloy IRs present a solution as they are biodegradable and have mechanical properties near that of bone. These qualities will mitigate the effects of stress shielding and reduce the risk of secondary surgeries.

Figure 1: **a)** Intramedullary rod placed in femur to stabilize fracture. **b)** Stress map of rod under loading during step.

Objectives

1. Design a component with the aim of improving bone remodeling in long bone fractures
2. Explore IR geometries with improved bone compatibility
3. Leverage Mg-alloys and topology optimization (TO) to develop an innovative biodegradable IR design
4. Conduct finite element analysis (FEA) to benchmark design performance
5. Use TO to tailor implant stiffness while minimizing volume

Methods

Dimensions: ~8mm Ø x 200mm L
Mg alloy corrosion: CR = ΔV/At
Corrosion Rates [mm/year]: -0.2, -0.5
Considered time intervals: 0-, 2-, 4-, & 6-months
Stiffness calculated at each time interval: axial compressive, flexural, torsional. Compared with bone, stainless steel, titanium alloy (Ti-6Al-4V)
Mg-1.0Zn-0.2Ca Elastic Properties: E = 45.2GPa, v = 0.338
Optimization Objective: Minimize strain energy
Constraint: 30% volume fraction
Software: Abaqus, Abaqus TOSCA, MATLAB, SolidWorks

Results

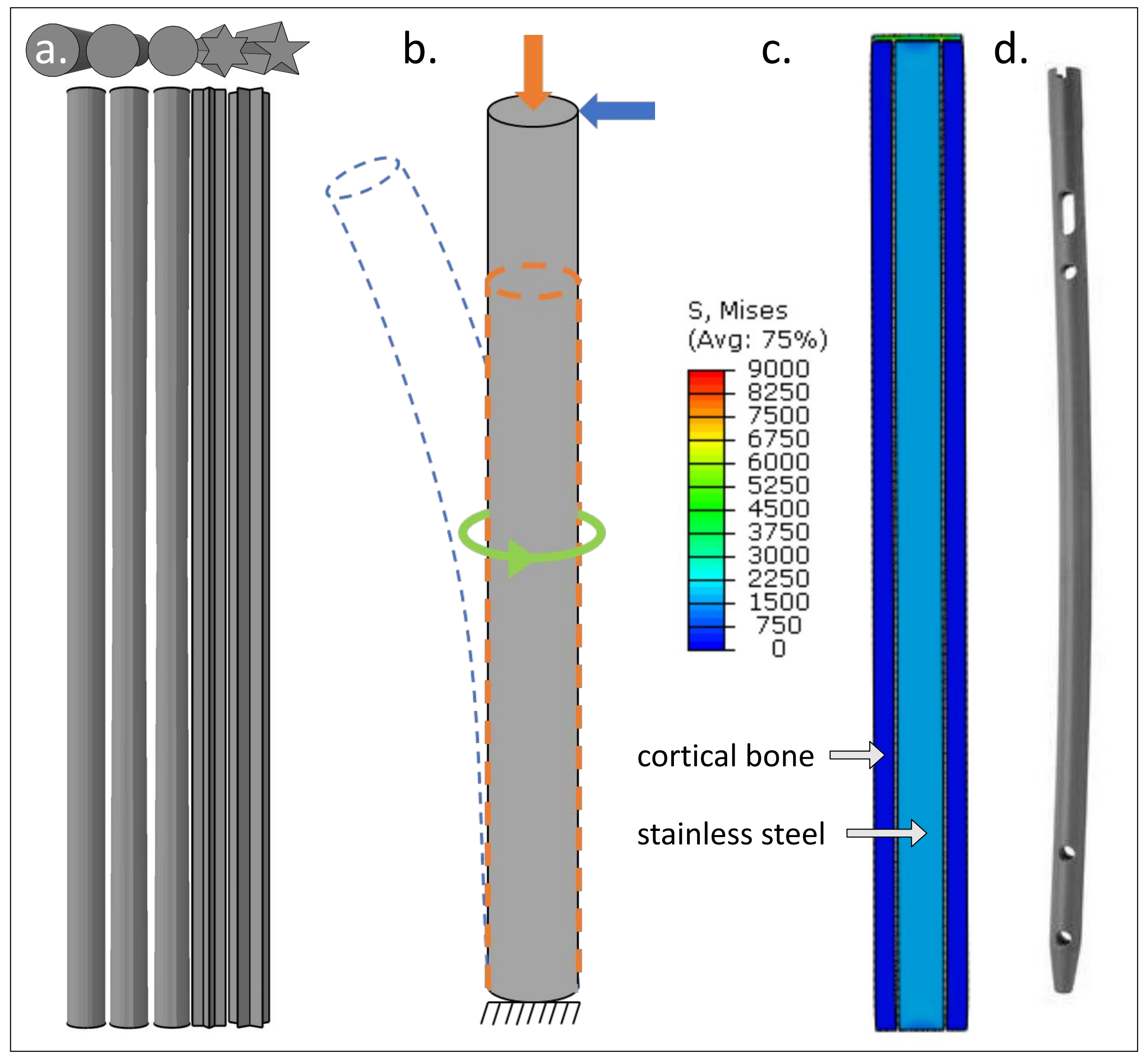
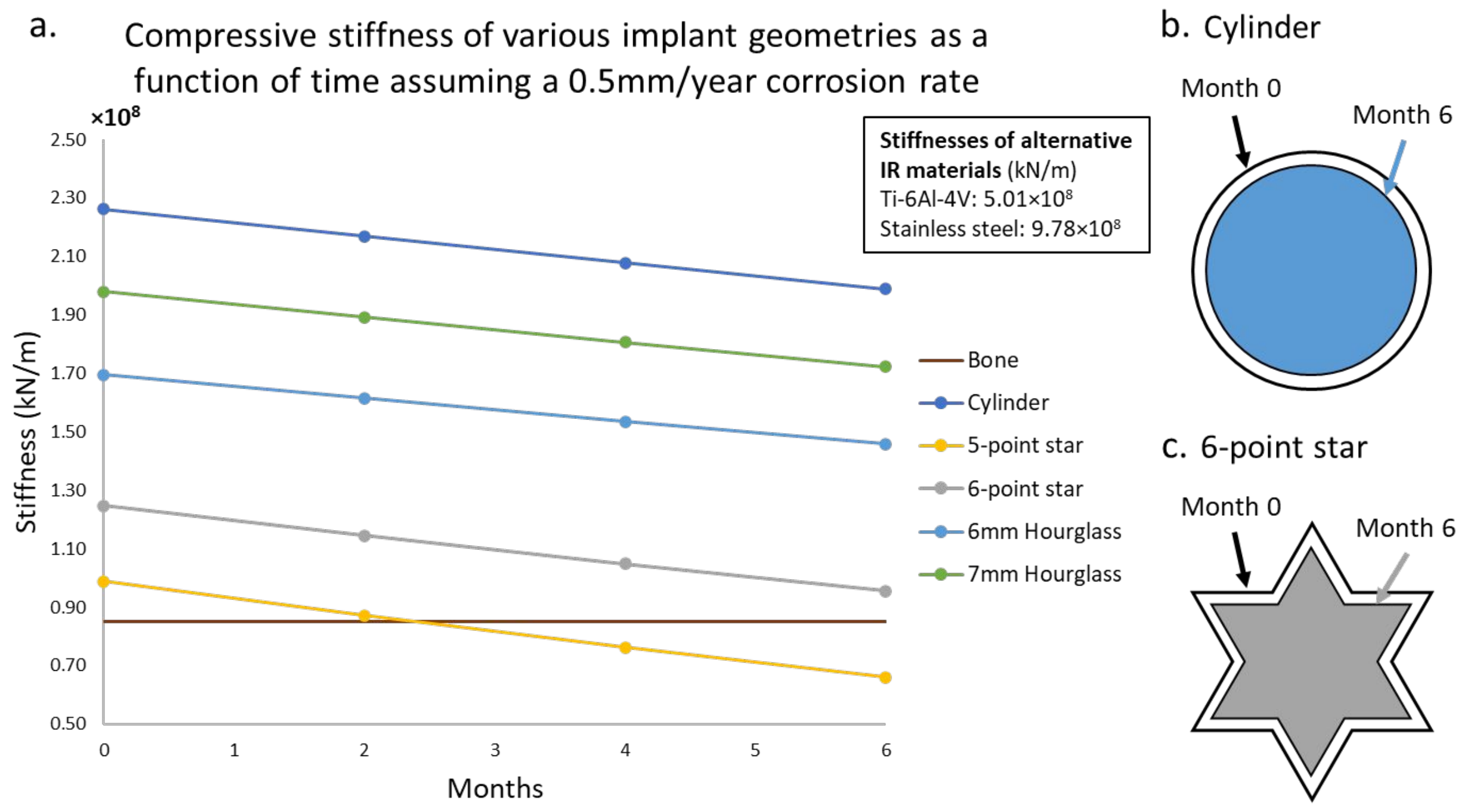


Figure 2: **a)** IR geometries considered in FEA performance models. **b)** Loading conditions tested to mimic *in vivo* environment of femoral long bone fracture. Orange corresponds with a 500N compressive load, Blue with a 100N flexural load, and Green with a three-radian torsional deformation. **c)** FEA stress shielding model. Longitudinal cross-section of concentric cylinders, outer cylinder adopts elastic properties of bone and inner cylinder adopts those of stainless steel. **d)** Image of conventional IR design



Stiffnesses of alternative IR materials (kN/m)
Ti-6Al-4V: 5.01×10⁸
Stainless steel: 9.78×10⁸

Figure 3: **a)** Compressive stiffness comparison between experimental IR geometries, bone and conventional implants. Experimental geometries were modeled at 0-, 2-, 4-, and 6-month snapshots to simulate degradation of the implant within the body. **b)** Modeled 6-month degradation of Mg-alloy cylindrical IR. **c)** Modeled 6-month degradation of Mg-alloy 6-point star IR.

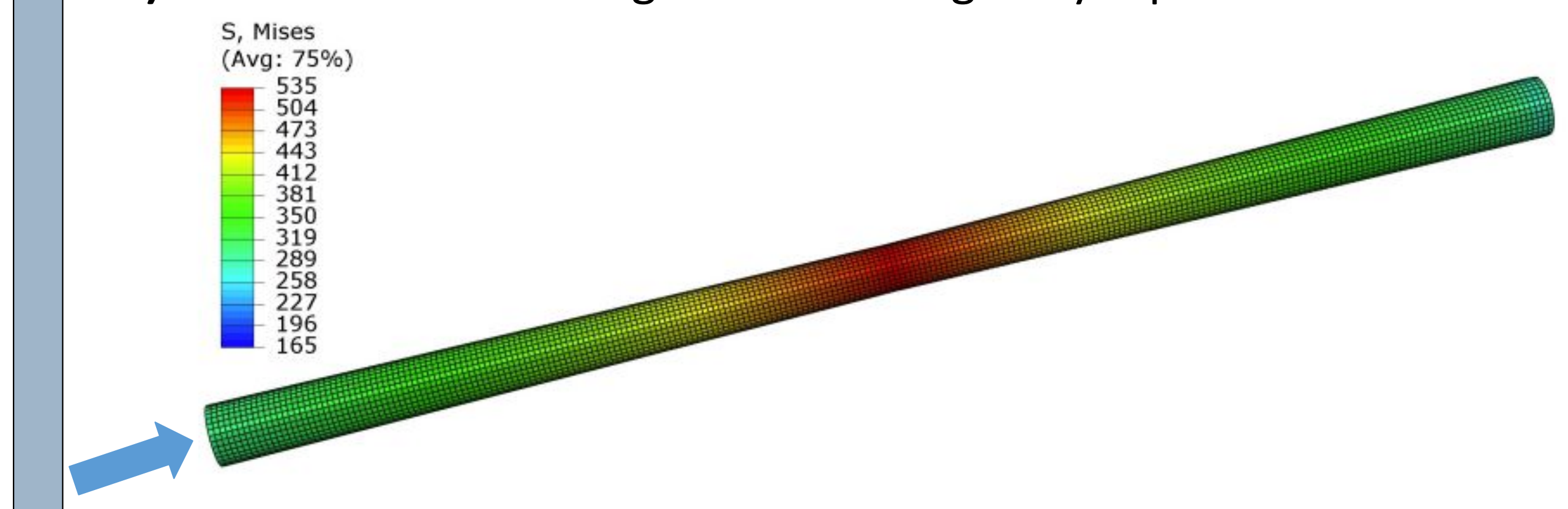


Figure 4: FEA stress map of hourglass-shaped IR (6mm center diameter) with 500N load applied in direction indicated by arrow.

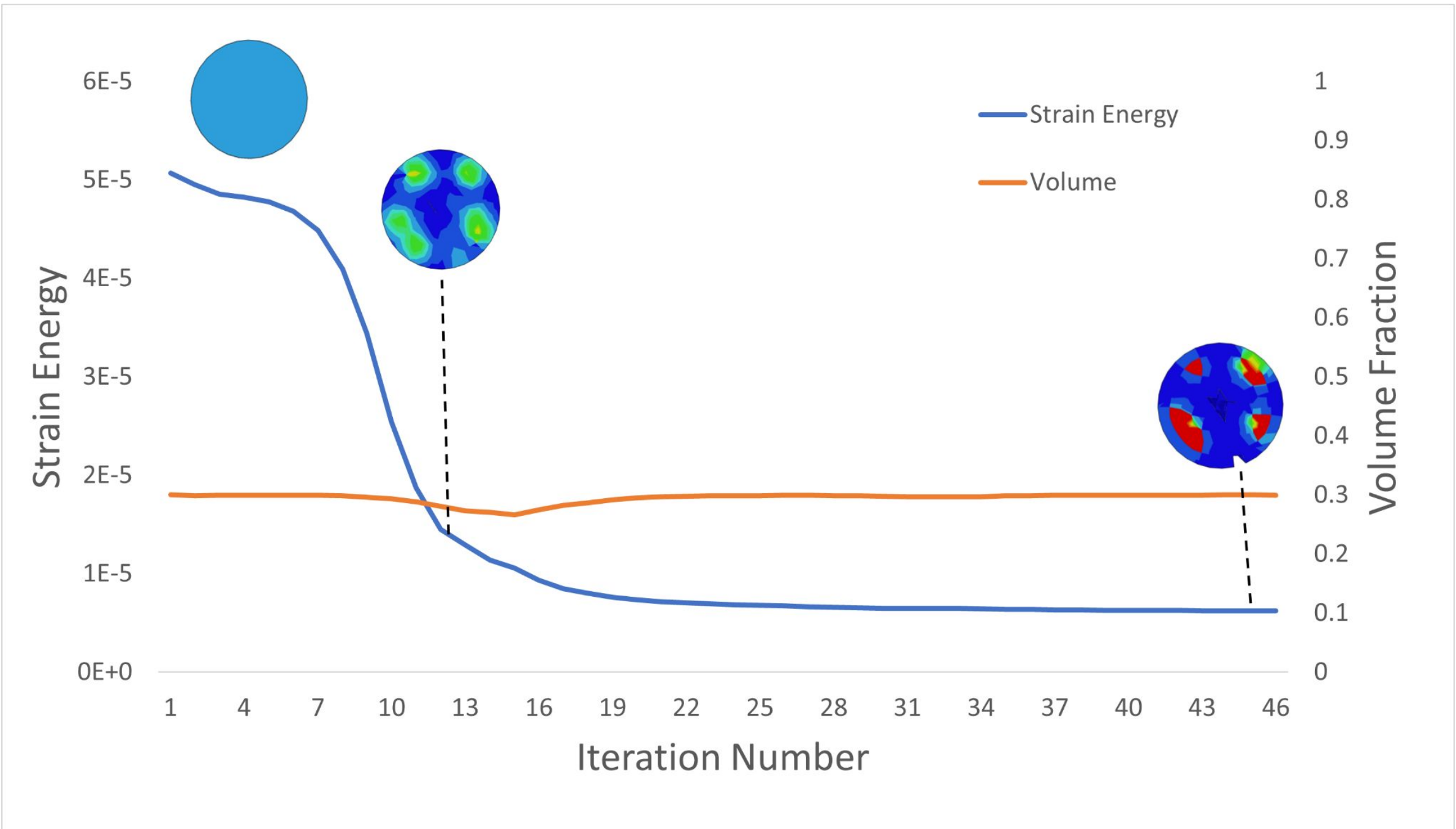


Figure 5: Plot of strain energy optimization process with a 30% volume fraction (constraint) using Abaqus optimizer. Cross-section of IR shown throughout optimization process at iterations 0, 12, and 45.

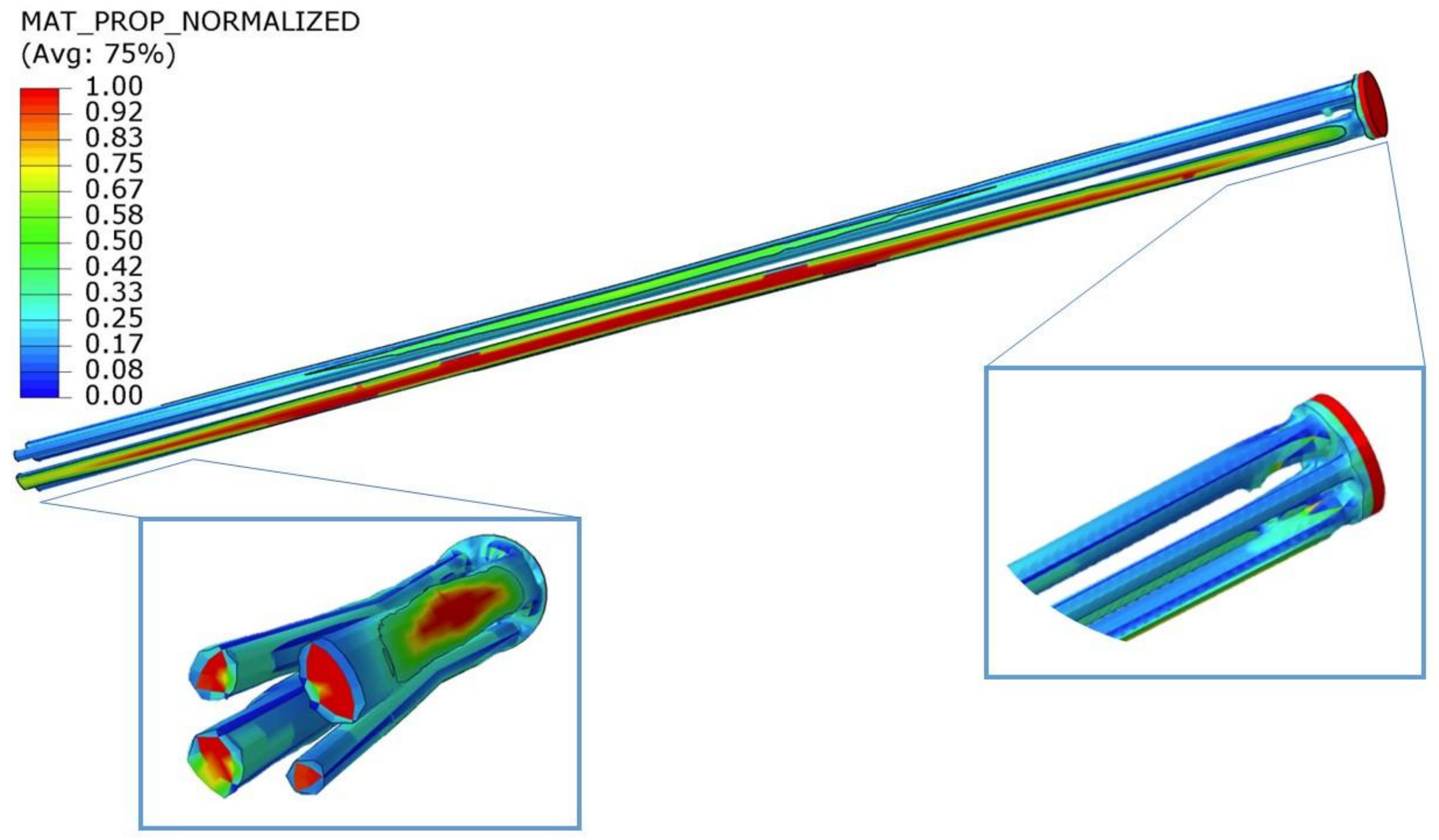


Figure 6: Topology optimization solution of an hourglass rod generated by ABAQUS. Resulting solution is a "stool" shape with four legs and a tapered center.

Figure 7: Optimization and corrosion of cylindrical IR generated by MATLAB. Colored dots represent models at various stages of degradation (Orange at 0 months, Yellow at 2 months, Green at 4 months, Blue at 6 months)

Conclusions

FEA indicates that an hourglass-shaped IR is a promising design for Mg-alloy intramedullary rods. TO solutions corroborate this finding and indicate that stool-leg ends would improve the rod's performance. Hourglass IRs exhibit slightly higher axial compressive and flexural stiffnesses than bone. In contrast, star-shaped rods demonstrate insufficient stiffnesses to provide stability during fracture healing.

Future Work

- Incorporate surrounding bone environment and IR fixation points into FEA modeling to more accurately predict *in vivo* behavior
- Consider buckling in FEA and TO under compression
- Improve corrosion rate modeling through continuous FEA degradation models and *in vitro* testing of Mg-Zn-Ca
- Develop more complex TO models with degradation optimization capabilities using MATLAB

Figure 8: Longitudinal cross-section of FEA model of the IR in the bone environment with fixation points at the top and bottom of the rod.

Acknowledgements

We would like to thank our mentors Justin Unger, Jamie Guest, Tim Weihs, and Orla Wilson for their support and invaluable feedback throughout this process. We would also like to thank Alberto Torres and Michael Vladimirov for their support as we learned Abaqus and SolidWorks.

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