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The modelling and 3D printing of functionally graded foams for tunable crushing performance

S. Macrae Montgomery[1,*], Haley Hilborn[1], Craig M. Hamel[2], Xiao Kuang[1], Kevin N. Long[2], H. Jerry Qi[1]

[1] Woodruff School of Mechanical Engineering, Georgia Institute of Technology

[2] Sandia National Laboratories

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Outline

- Background/Motivation
- Goals
- Results
  - Numerical/experimental approach
  - Model fitting and comparisons
  - Design space exploration
- Conclusions

Acknowledgements

- Sandia National Labs
- AFOSR, FA-20-1-0306, FA9550-19-1-0151.

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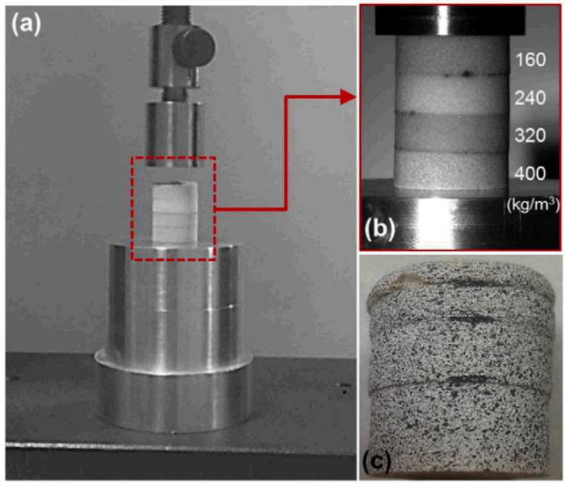
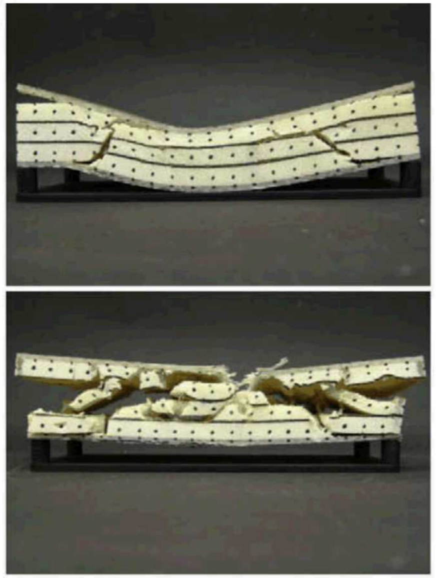
Motivation

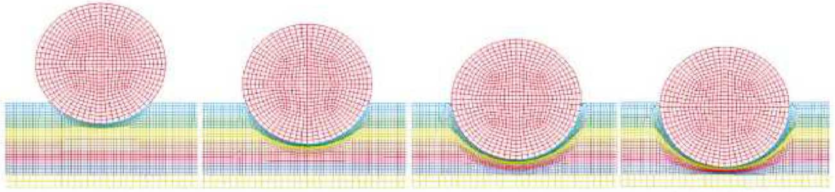
- **Most safety/packaging applications require designing for a variety of impact scenarios**
- **FGFs are introduced to overcome limitations of uniform foams**
- **FGFs have their own limitations**
  - **Little microstructural control, limited to simple gradients, large design space, hard to model accurately**



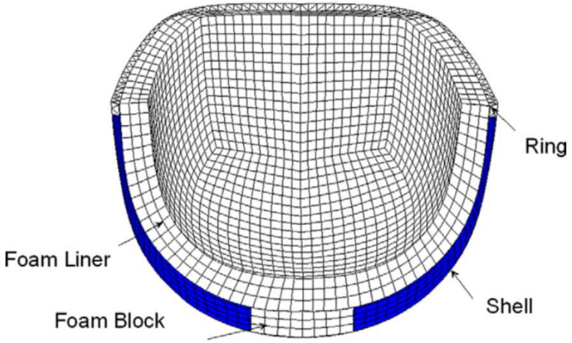
[1] Koohbor and Kidane (2016)



[2] Wang *et al.* (2009)



[4] Zhang and Zhang (2013)



[3] Cui *et al.* (2009)

Grayscale Digital Light Processing (g-DLP)

- **In DLP, a projector shines light onto a build platform submerged in resin**
- **Build platform is slowly lowered into the resin, building the final part layer-by-layer**
- **The brightness of each image will determine the material properties**

[5] Kuang *et al.* (2019)

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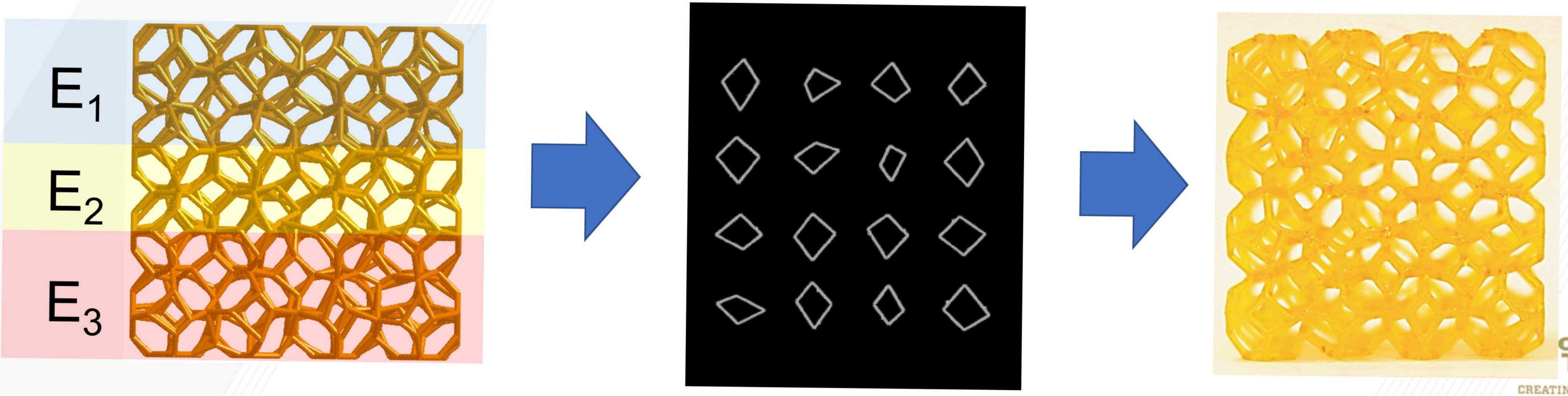
Goals

- Develop a numerical model that can accurately predict the response of 3D-printed viscoelastic foams
- Use this model to better understand the benefits of FGFs
- Use this model to explore the graded foam design space
- Display its usefulness as a design guide to select the right foam for a certain use case

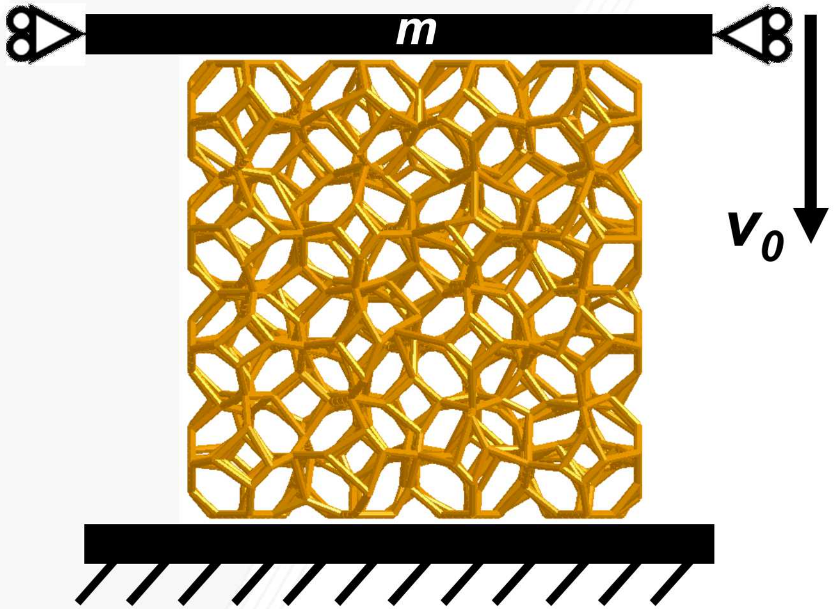
Grayscale Foam Structure

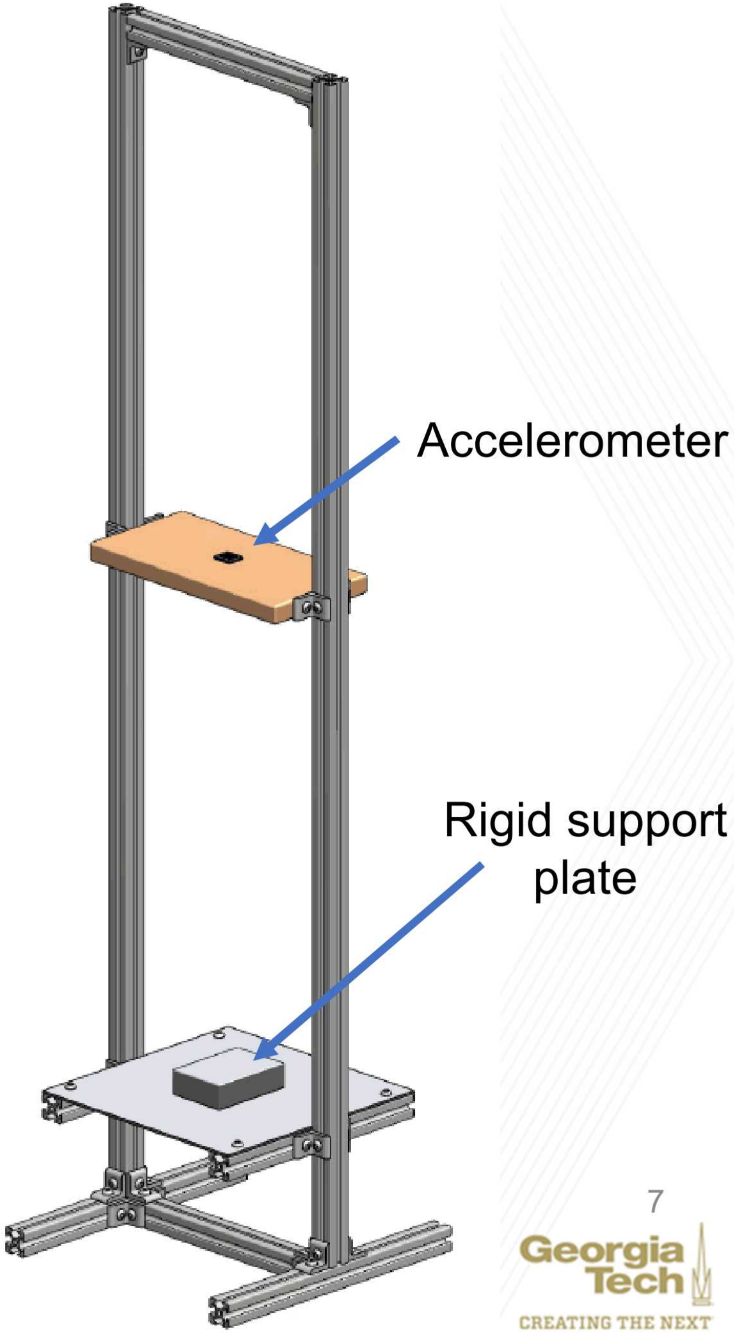
- Modeled as Kelvin cells with uniform circular beam cross-sections
- Arranged as 4x4x4 cell RVEs
- Cell vertices are randomly perturbed
- Graded foams are assigned 3 properties



Testing Configuration

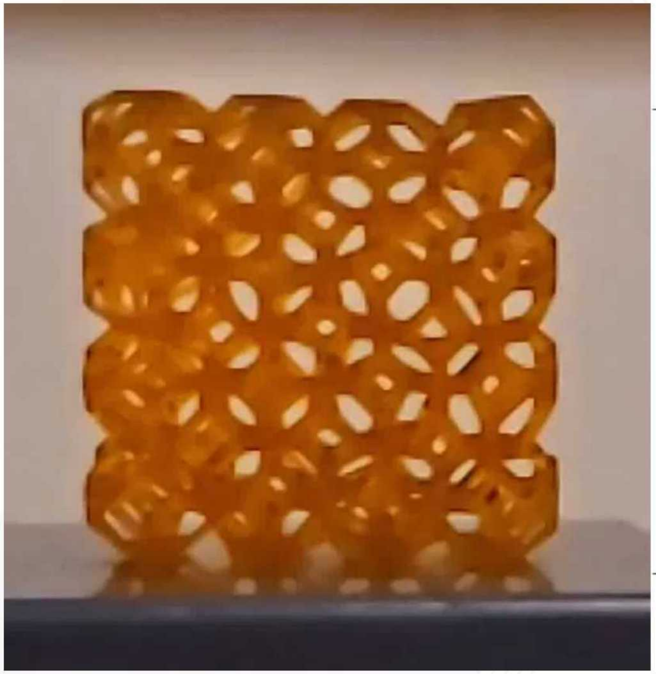
- A plate of prescribed mass m and initial velocity v_0 is dropped onto a foam
- Bottom plate has a rigid boundary
- In the experimental setup, the mass is fixed, and the velocities represent a height of 1ft or 3ft

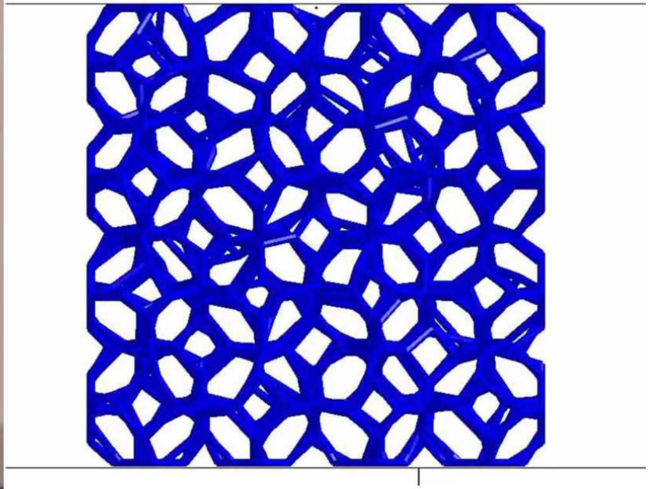




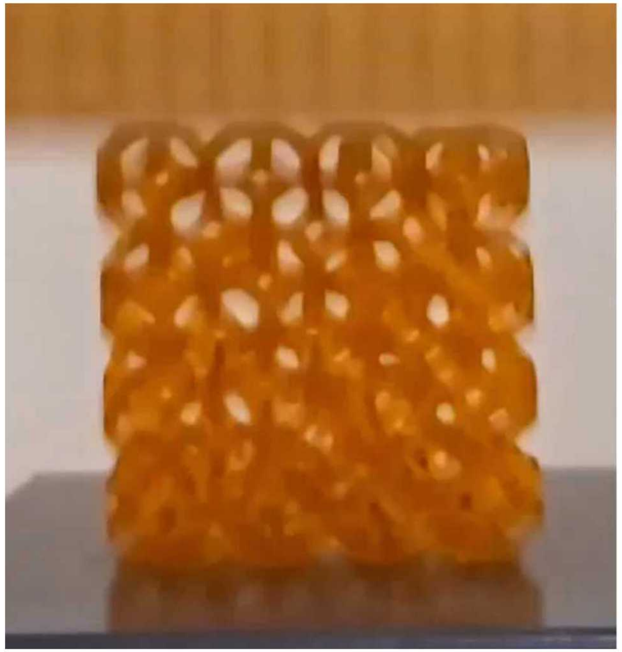
Model Qualitative Comparisons

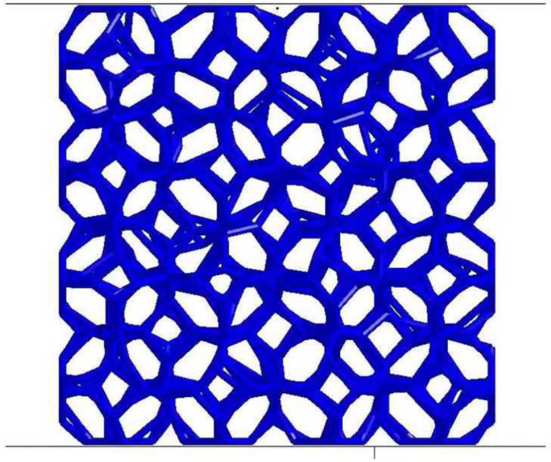
4.23m/s





2.44m/s

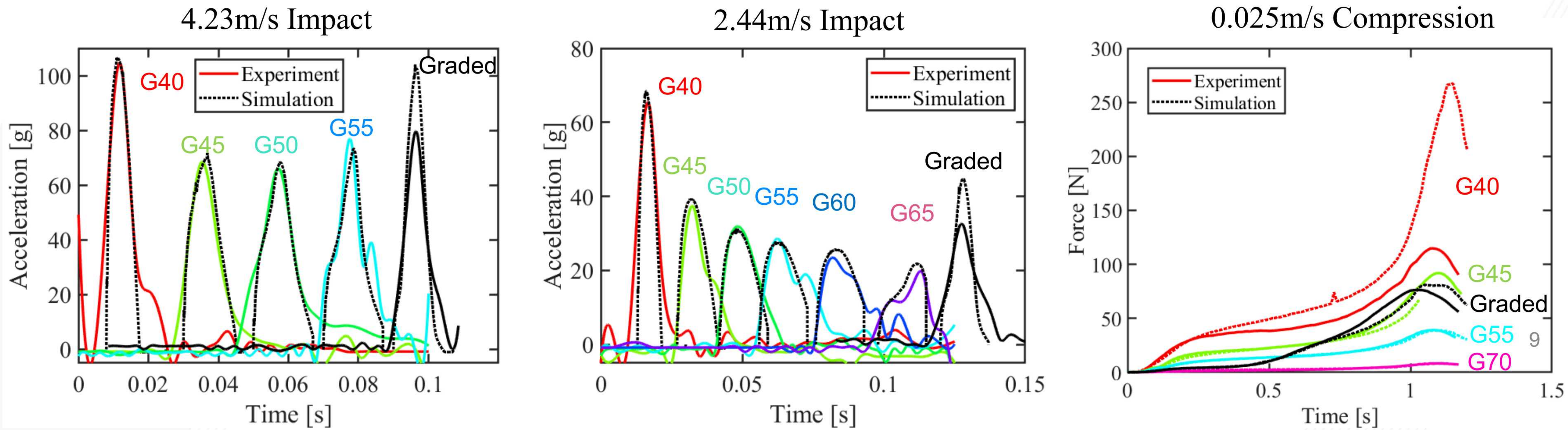




Model Quantitative Comparisons

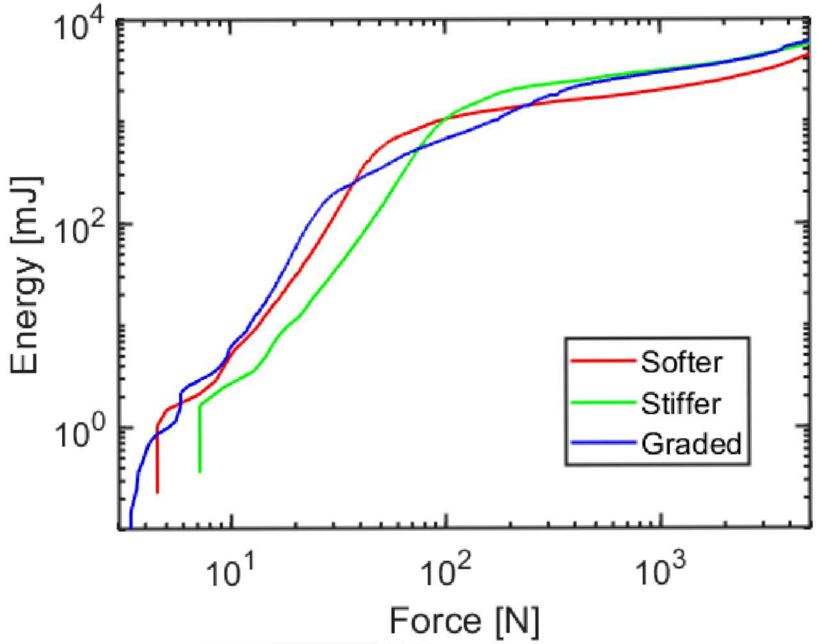
- **The viscoelastic data is fit to the model at multiple strain rates**
  - **170x difference in fastest and slowest rates**

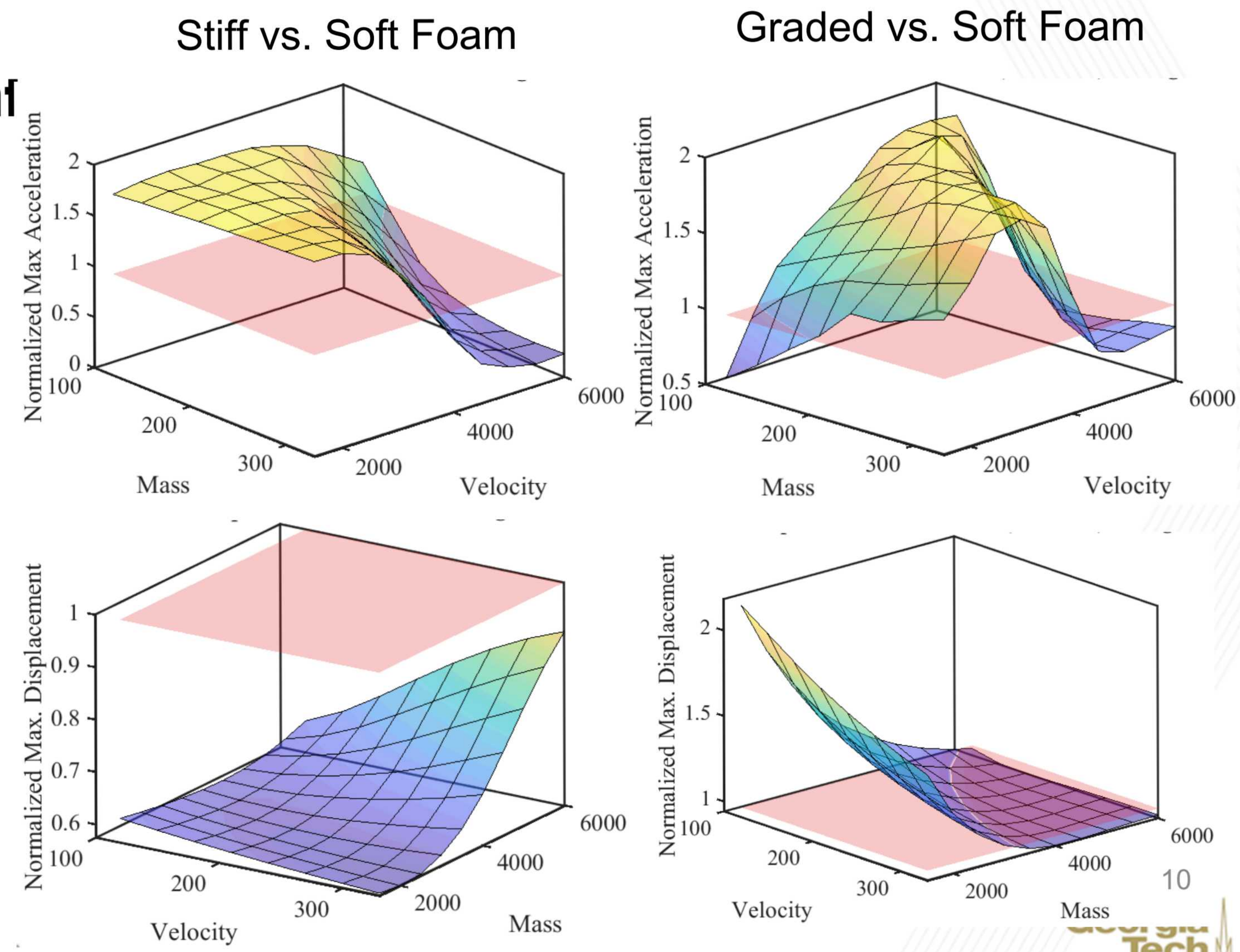
- **This strong agreement gives us confidence in our properties**



Exploring the Design Space

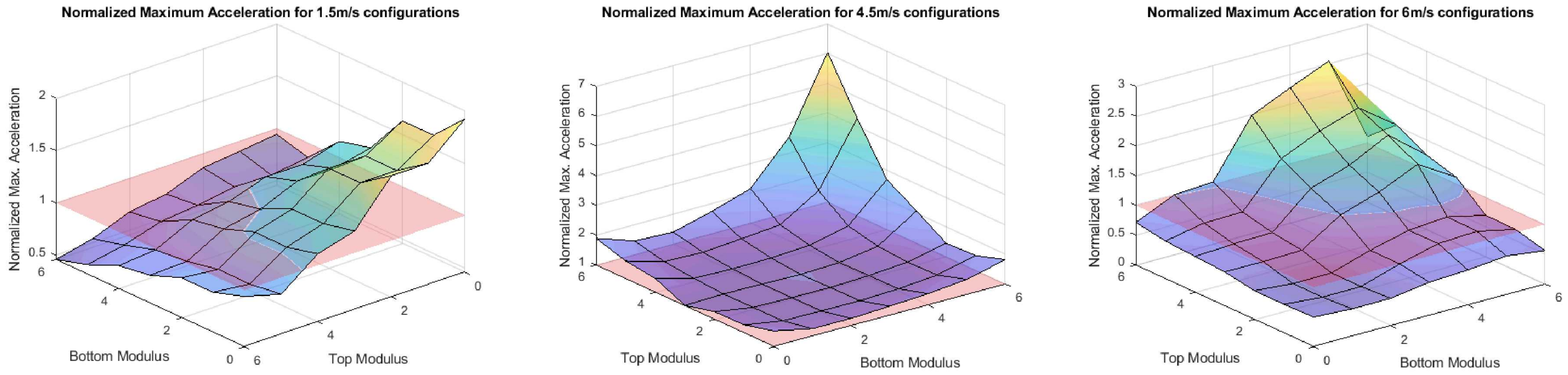
- **This accurate model give us insight the performance of graded foams**





Design Application

- **The accurate model allows us to also explore graded configurations we have not printed and compare them**

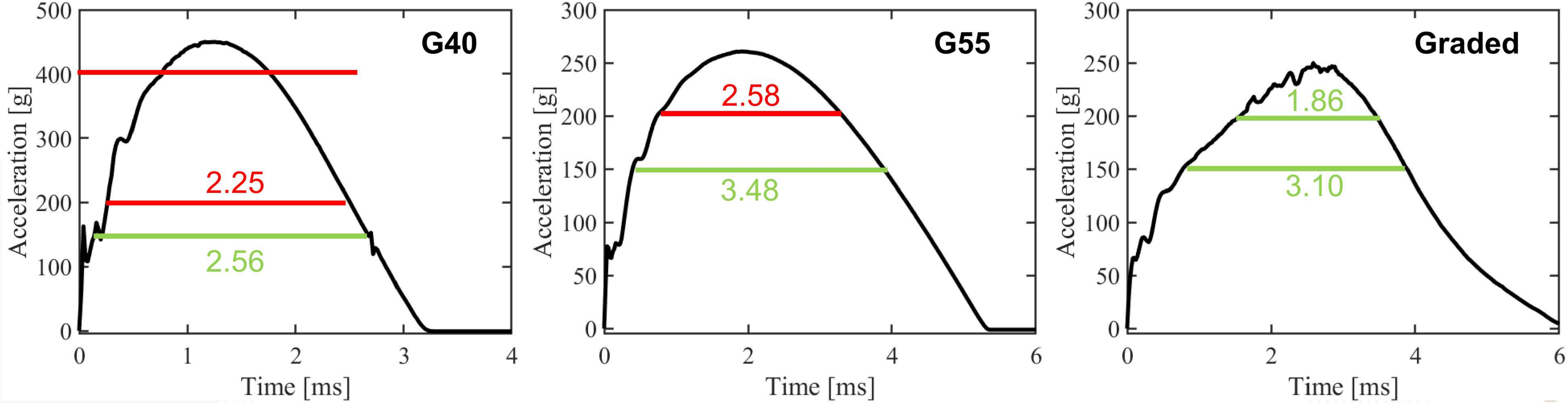


Helmet Design Scenario

- **Simulations Performed in accordance with National Highway Traffic Safety Administration (NHTSA) Test Procedure TP-218-07**

Test Parameters	
Mass	4.9 – 5.1kg
Velocity	5.8 – 6.2m/s
400g Limit	0ms
200g Limit	< 2ms
150g Limit	< 4m/s

[6] TP-218-07 (2011)



Conclusions

- A beam element model can be used to accurately predict highly viscoelastic foam responses across wide range of strain rates

- Property gradients decrease the maximum efficiency but extend the effective range of foams

- This model can be used to explore the design space to predict relative performance like a design guide

Citations

1. Koohbor, B. and A. Kidane (2016). "Design optimization of continuously and discretely graded foam materials for efficient energy absorption." Materials & Design 102: 151-161.
2. Wang, E., et al. (2009). "The blast resistance of sandwich composites with stepwise graded cores." International Journal of Solids and Structures 46(18): 3492-3502.
3. Cui, L., et al. (2009). "Optimisation of energy absorbing liner for equestrian helmets. Part II: Functionally graded foam liner." Materials & Design 30(9): 3414-3419.
4. Zhang, X. and H. Zhang (2013). "Optimal design of functionally graded foam material under impact loading." International Journal of Mechanical Sciences 68: 199-211.
5. Kuang, X., et al. (2019). "Grayscale digital light processing 3D printing for highly functionally graded materials." Science Advances 5(5): eaav5790.
6. (2011). LABORATORY TEST PROCEDURE FOR FMVSS No. 218 Motorcycle Helmets. D. o. Transportation, Office of Vehicle Safety Compliance

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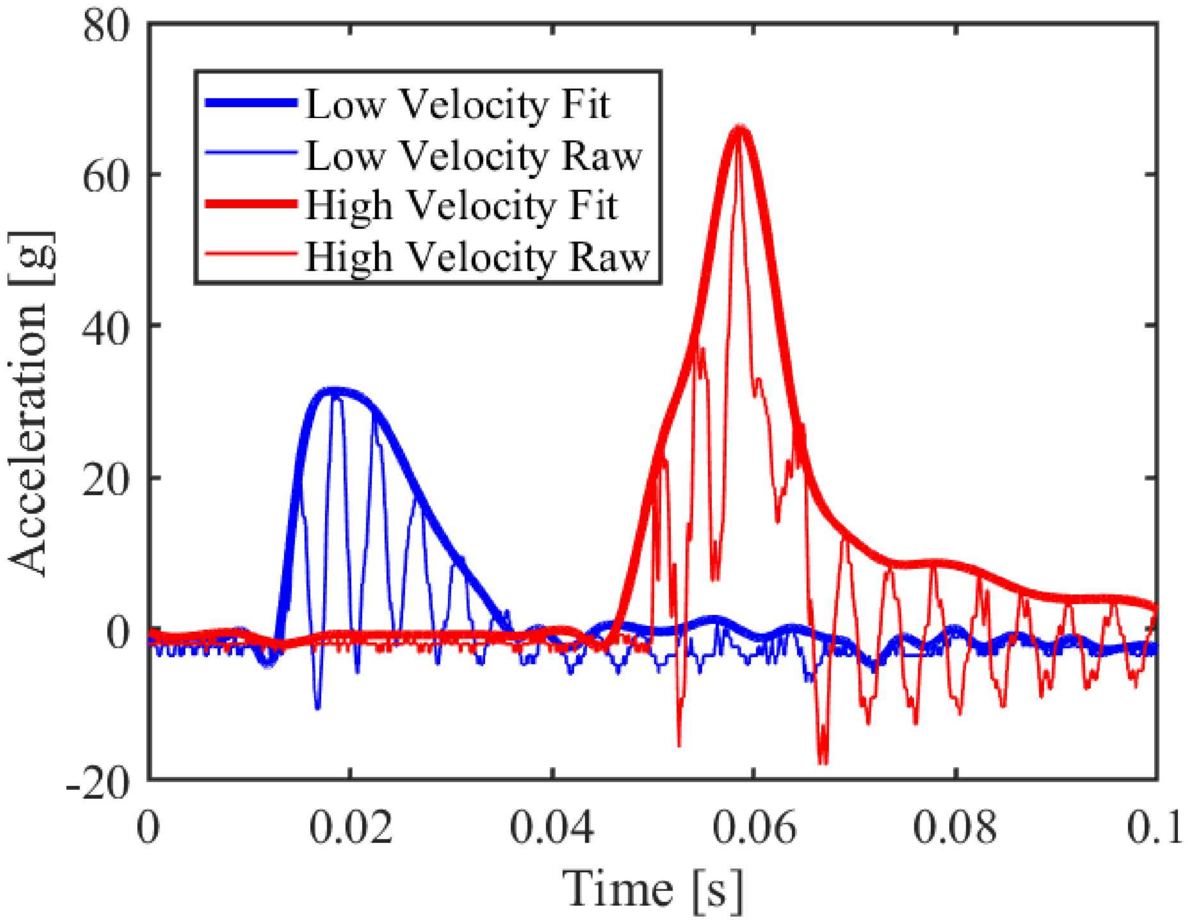
Thank you!

Questions?

Appendix

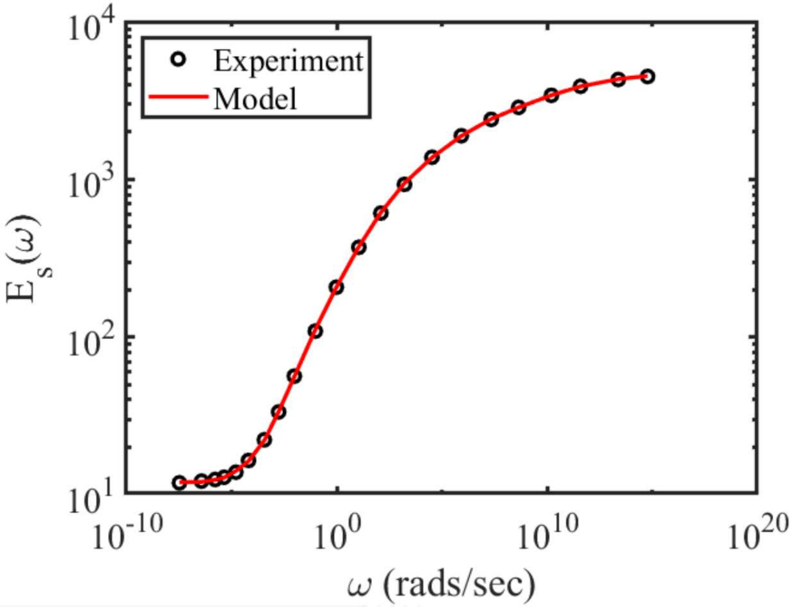
Acceleration Data Fitting

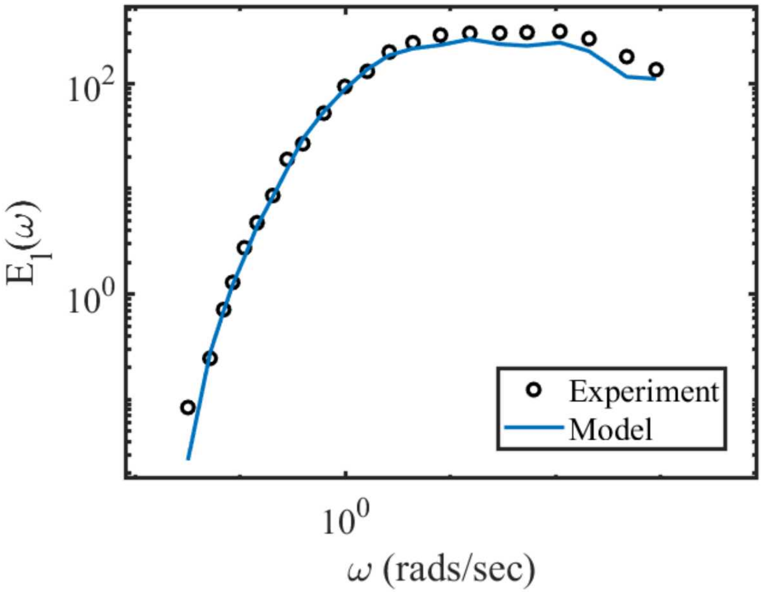
- **Envelope function in MATLAB with window of 30 points**

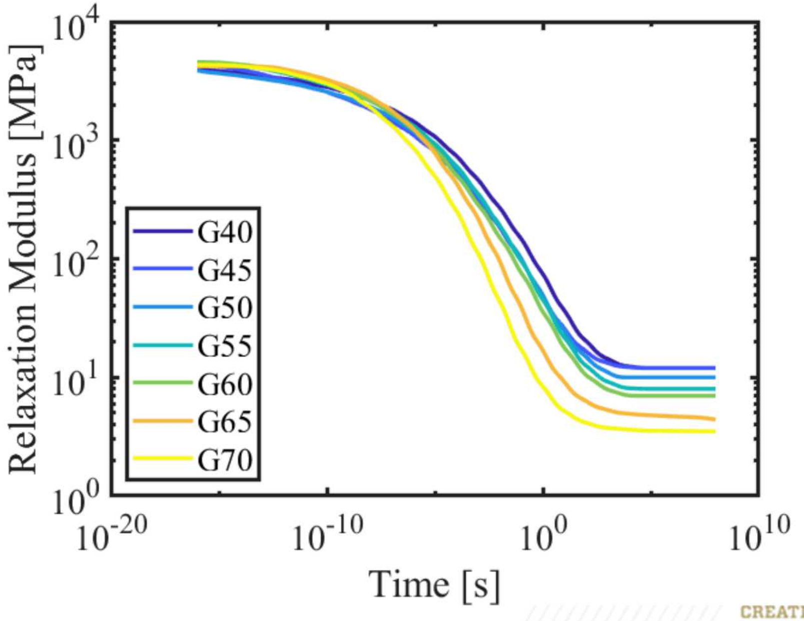


Material Property Characterization

- **Individual grayscale materials analyzed under frequency sweep**
- **The Prony series branch moduli were determined by fitting the frequency-dependent storage and loss moduli**

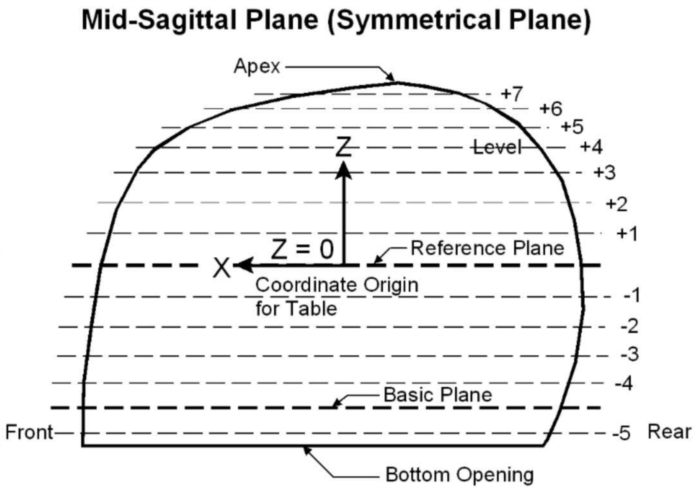


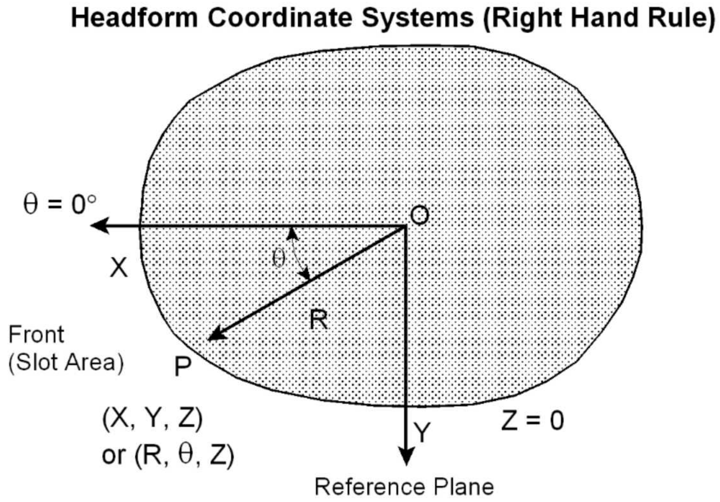


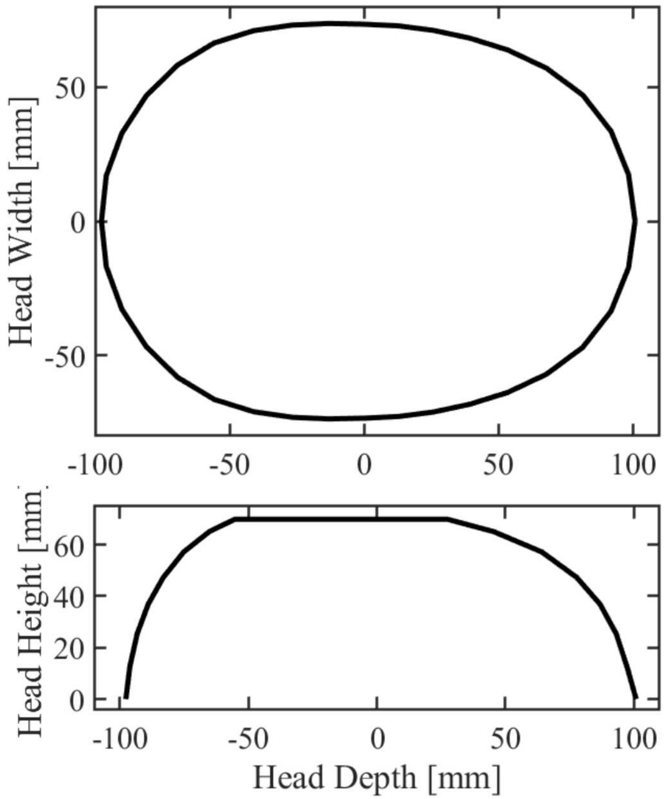


Headform size calculations

- **Top area is calculated as the area of the headform at the reference plane**
- **Side area is calculated as the profile area above the reference plane**







[6] TP-218-07 (2011)

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