Honeycomb Unit Cell Optimization using Parametric Analysis

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Dedicated this work to my parents, all the group members, and one of the bests ever worked with, Dr. Bhate!

Outline

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  - Designing in SpaceClaim
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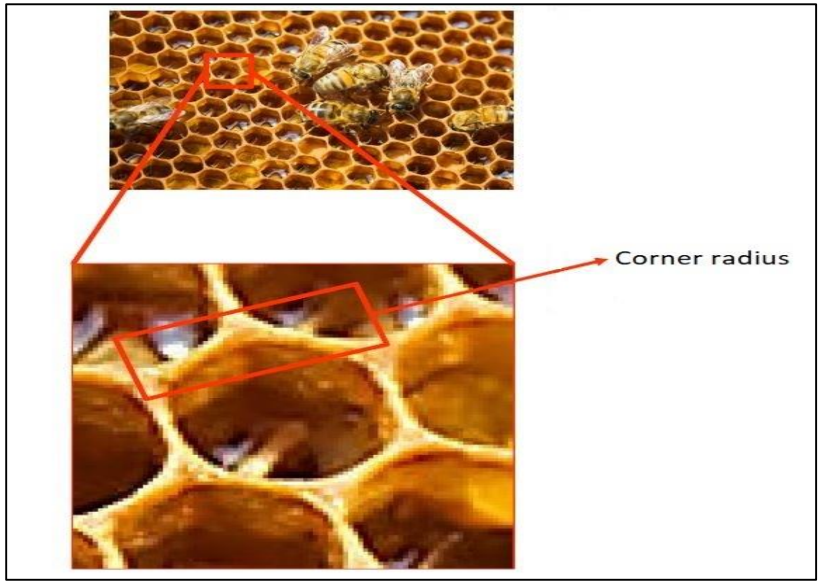
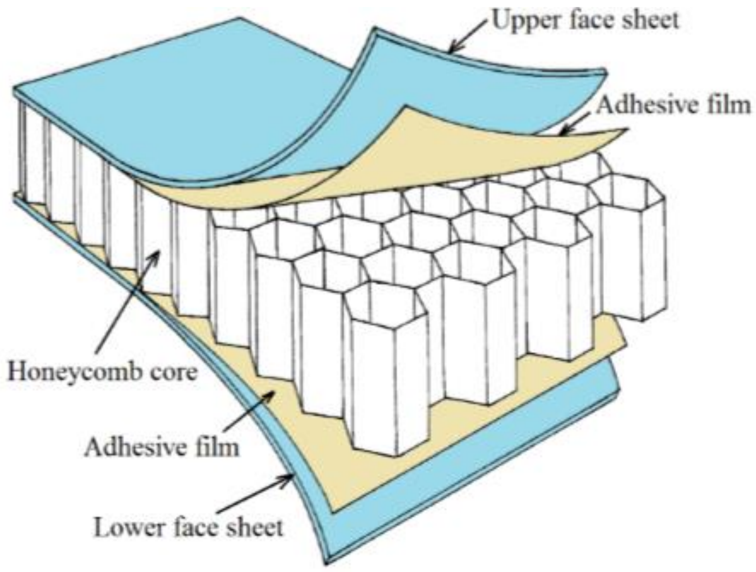
About Honeycomb

- Hexagonal prismatic wax cells built by honey bees
- Used as the cores of sandwich panels in the aerospace, automotive, and many more industries
- Efficient for resisting bending and buckling loads



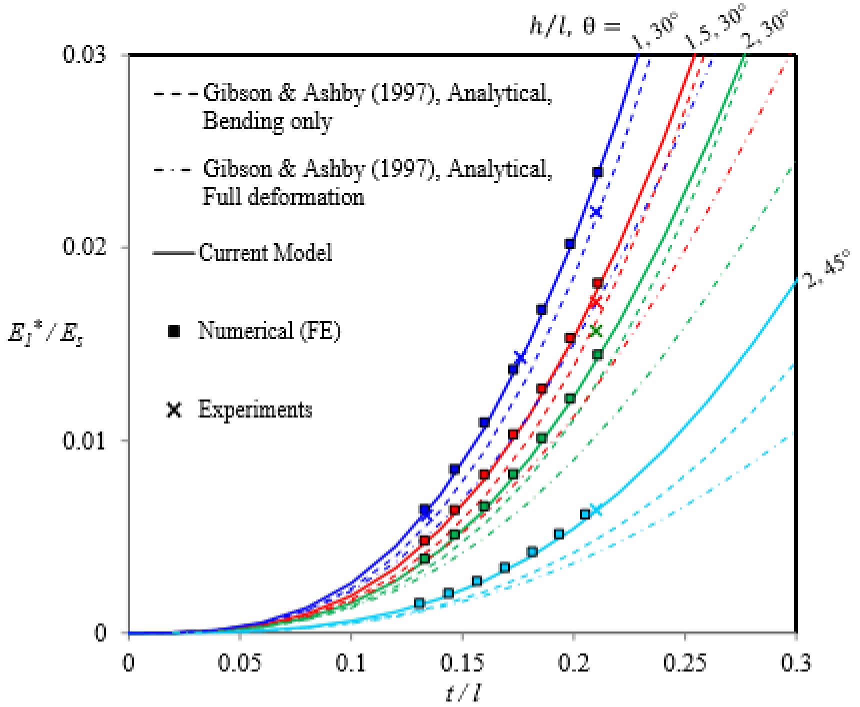
Natural Honeycombs [8]

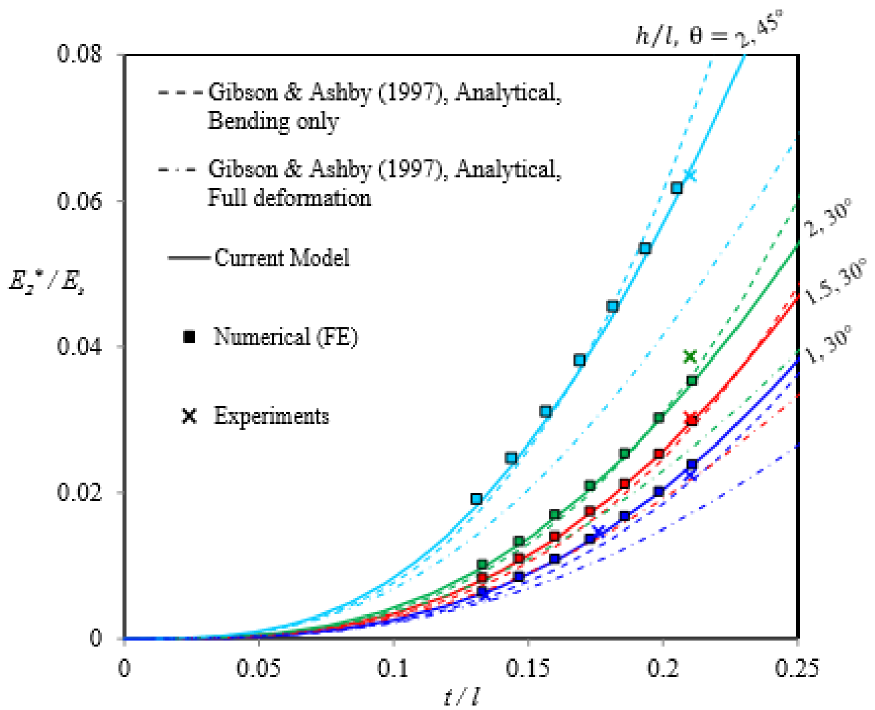


Honeycomb Panel [3]

Literature Review

- Malek and Gibson [2] investigated the elastic behavior of periodic hexagonal honeycombs over a wide range of relative densities and cell geometries, using analytical and numerical approaches.

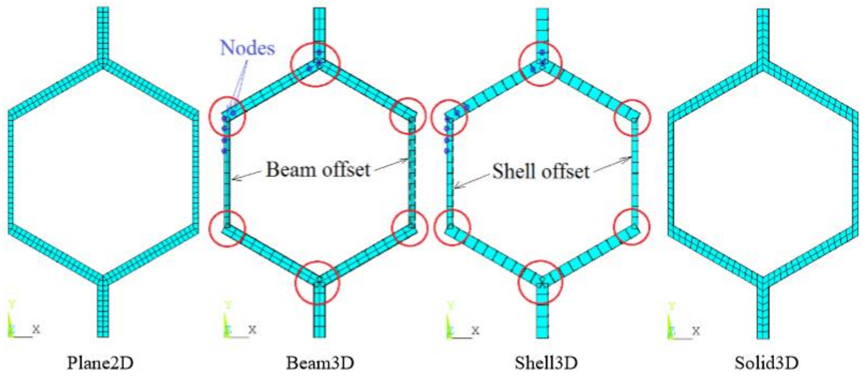




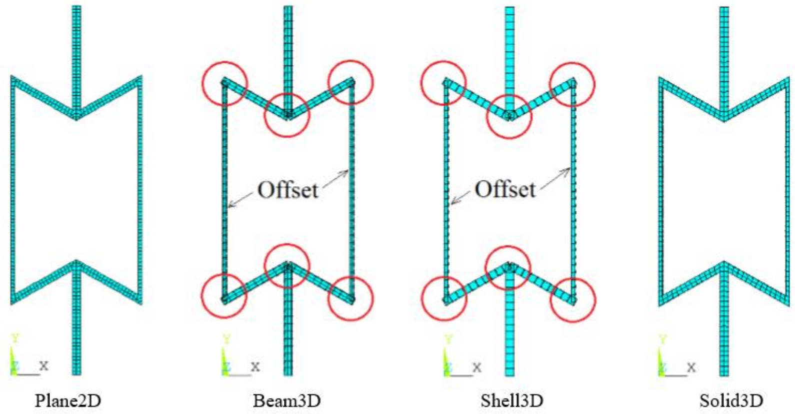
Effective Young's modulus in the X_1 and X_2 directions. Predictions are given for different cell wall geometries

Literature Review (Continue)

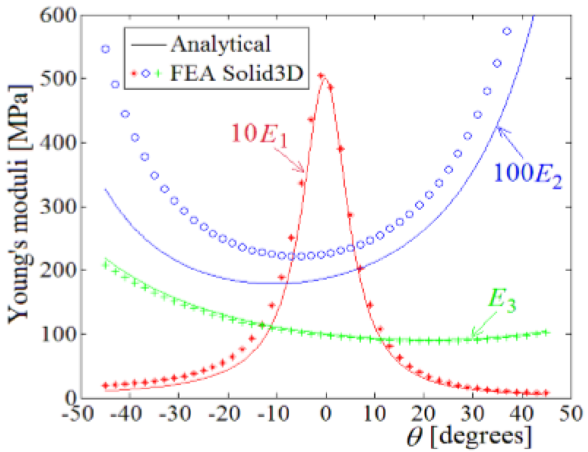
- Sorohan, et. al., [3] presented the 2D and 3D FE models to study the equivalent orthotropic mechanical properites of honeycombs.



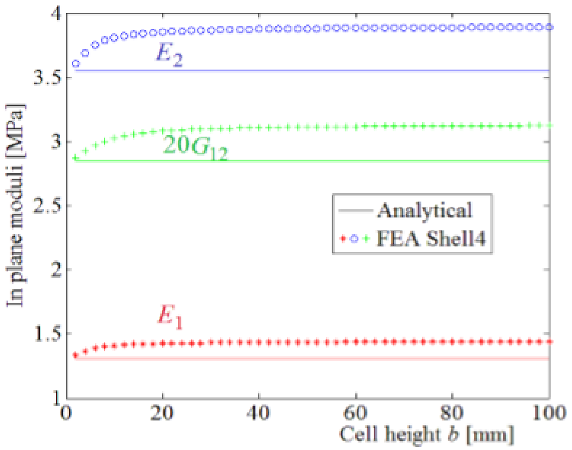
Discretization of the regular hexagon RVE



Discretization of the re-entrant classical honeycomb RVE



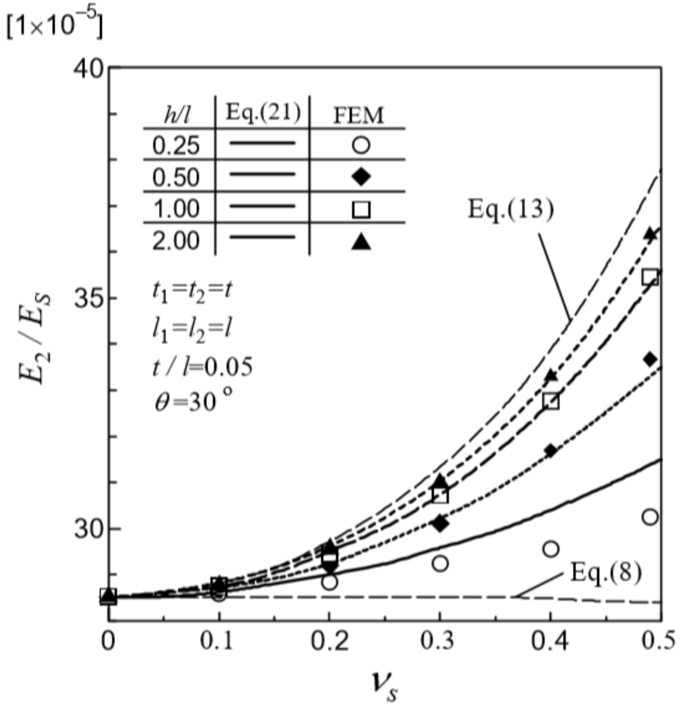
Young's moduli v/s internal cell angle



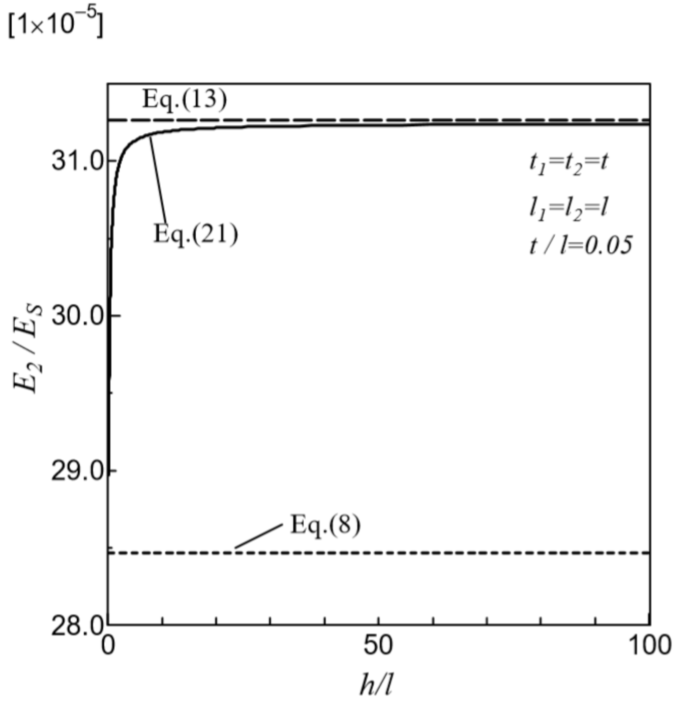
In-plane moduli v/s cell height (depth) variation

Literature Review (Continue)

- Chen and Ozaki [4] used the FE method to investigate the influence of core height on the in-plane effective Young's modulus. They clarified (for the X_2 direction) that the cell walls deform in the height direction due to the Poisson's effect.
- They also showed that the analysis of honeycomb core is independent of height under the plane strain condition.



Elastic modulus v/s Poisson's ratio for regular hexagon honeycomb



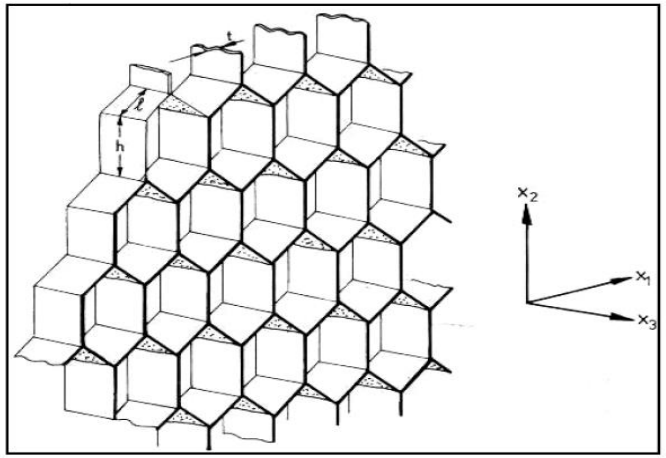
Elastic modulus v/s height of honeycomb core for Poisson's ratio 0.3

(For equations, refer [4])

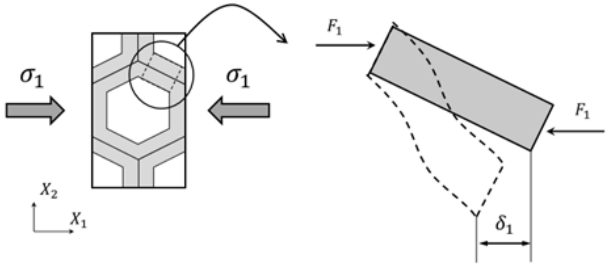
Mechanics

- The effective Young's modulus in the X_1 direction can be calculated as [2] –

$$E_1^* = E_s\left(\frac{t}{l_b}\right)^3 \frac{\cos\theta}{(h/l+\sin\theta)\sin^2\theta}\left[\frac{1}{1+\left(2.4+1.5\nu_s+\cot^2\theta\right)\left(\frac{t}{l_b}\right)^2}\right]$$



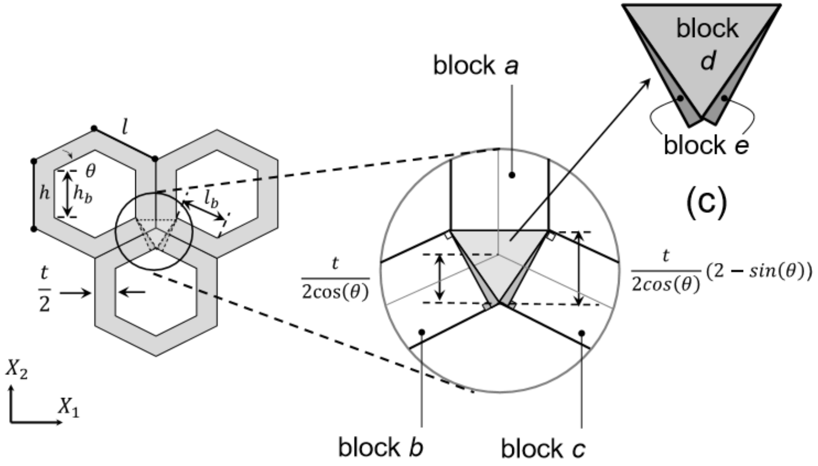
Honeycomb with hexagonal cells [1]



Hexagonal honey under loading in X_1 direction [2]

where, E_s = Young's modulus of material
ν_s = Poisson's ratio of material
σ_1 = stress in the X_1 direction
F_1 = applied force to each inclined member
δ_1 = deflection in the X_1 direction

- This project work focuses on the properties in the X_1 direction only.



Effective bending lengths of the cell wall for periodic hexagonal honeycombs [2]

Research Question

- How does the corner radius of the hexagon cell affect the mechanical properties of the 3D honeycomb cell?

- What can be the optimized value of hexagon parameters that can give a safe value of the maximum von-Mises stress in the honeycomb cell?

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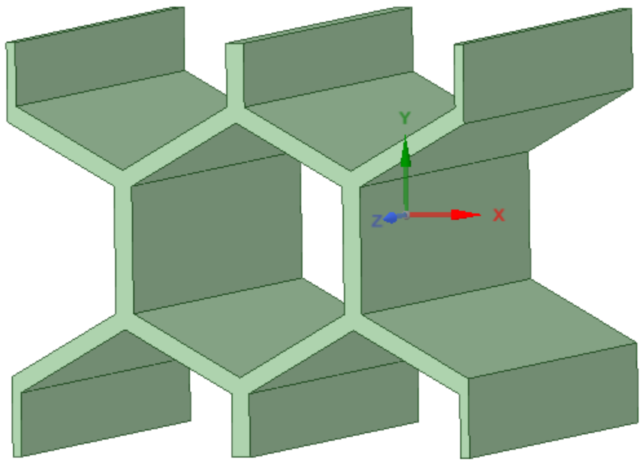
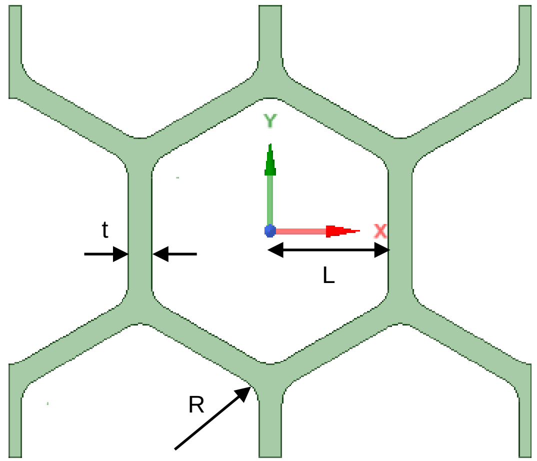
Designing in SpaceClaim

- A unit cell that can be represented as a representative volume element was designed using the SpaceClaim, a design interface of ANSYS (version 2019 R3 is used).

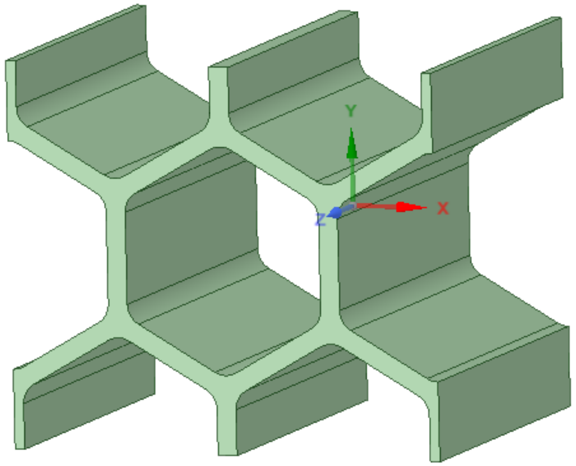
- Python script was recorded while designing the cell.



Honeycomb cell without corner radius



Front view of Honeycomb cell with radius



Honeycomb cell with corner radius

- The cell was designed in terms of only three parameters, inner circle radius (L), cell thickness (t), and inner hexagon corner radius (R). (here, L = 8.16 mm, t = 1.6 mm, R = 1.8 mm, and depth = 30 mm)

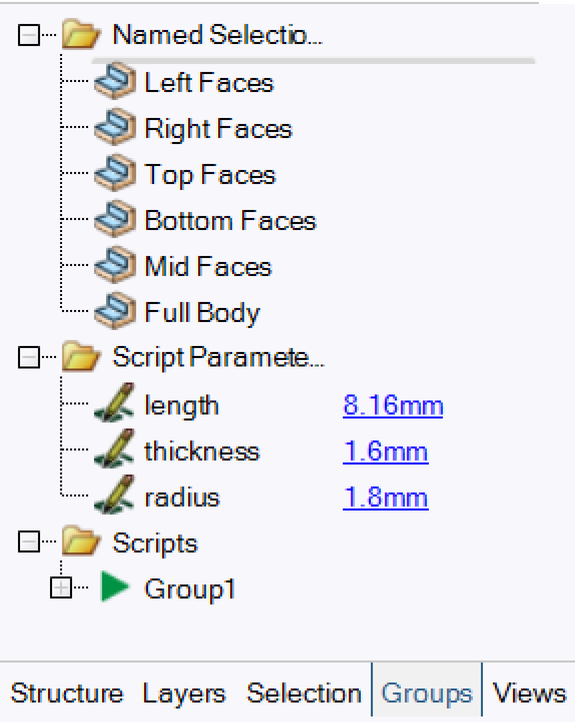
- There are certain restrictions in the Python script for the values of the parameters.

Parametrization of Input Parameters

- The Python script was grouped with the design such that the geometry can get updated with the variation in the input parameters.

```python
# Python Script, API Version = V18

# Delete Objects
while GetRootPart().Components.Count > 0:
  GetRootPart().Components[0].Delete()
while GetRootPart().Bodies.Count > 0:
  GetRootPart().Bodies[0].Delete()
while GetRootPart().Curves.Count > 0:
  GetRootPart().Curves[0].Delete()

HC_len = Parameters.length*1000
HC_thick = Parameters.thickness*1000
HC_rad = Parameters.radius*1000

# Set Sketch Plane
sectionPlane = Plane.PlaneXY
result = ViewHelper.SetSketchPlane(sectionPlane, Info1)
# EndBlock

# Sketch Polygon
startVertex = Point.Create(MM(0), MM(0), MM(0))
endVertex = Point.Create(MM(HC_len), MM(0), MM(0))
useInnerRadius = True
numSides = 6
```

Part of python script from SpaceClaim

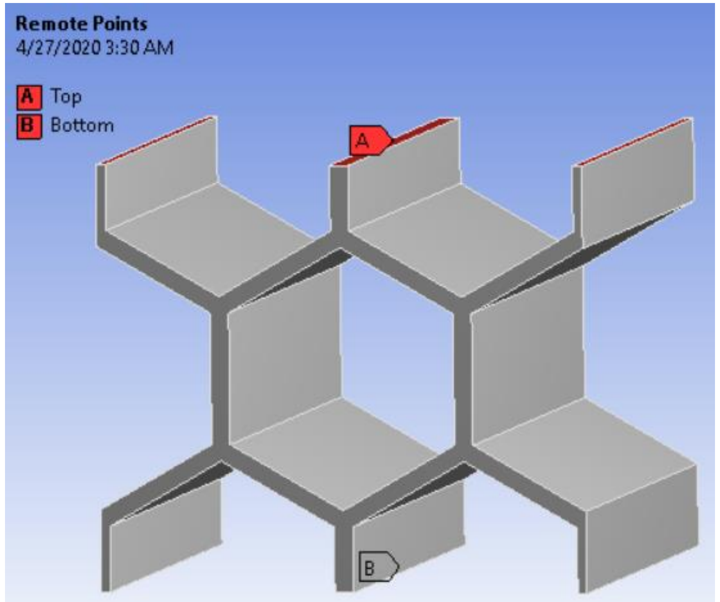


Names Selection, Parameters, and Group

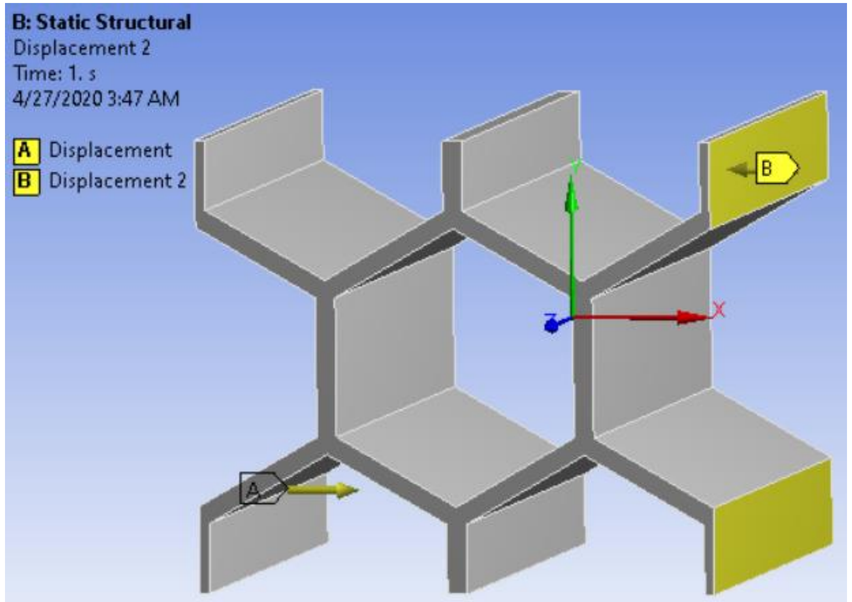
- Named selections were created for the boundary condition in the Workbench.

Boundary Conditions

- Periodic boundary conditions were used using coupling equations that can represent the structure with the multiple cells in both the directions (X_1 and X_2)



Remote Points



Displacement on left and right faces

Details of "Displacement 2"

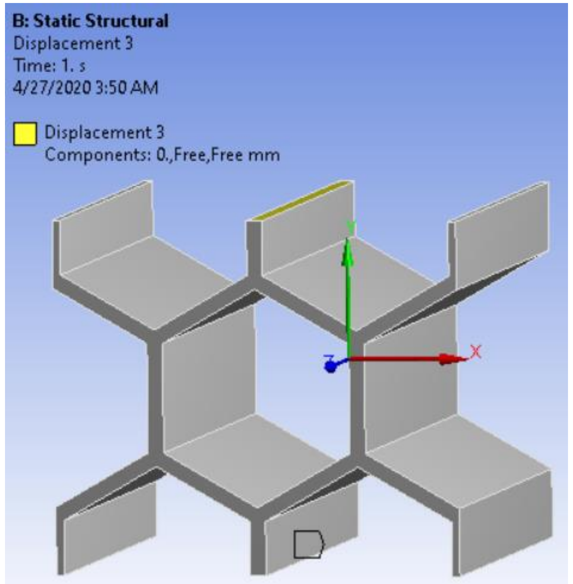
Scope	
Scoping Method	Named Selection
Named Selection	Right face
Definition	
Type	Displacement
Define By	Components
Coordinate System	Global Coordinate System
X Component	-0.3 mm (ramped)
Y Component	Free
Z Component	0. mm (ramped)
Suppressed	No

Displacement condition

- To compress the cell in the X_1 direction, displacement of 0.3 mm was given from both the sides to keep the strain under less (< 2.5 %) such that the model does not go in non-linear deformation.

Boundary Conditions (Continue)

- To maintain the symmetric deformation, following boundary condition was given:
  - X-displacement was zero at the top and bottom mid faces
  - It helps in preventing rigid body motion



Symmetric Deformation

- **Constraint Equations** (Coupling between top and bottom faces)

Constraint Equation

0 = 1 (1/mm) * Top(Y Displacement) + 1 (1/mm) * Bottom(Y Displacement)

Coefficient	Units	Remote Point	DOF Selection
1	1/mm	Top	Y Displacement
1	1/mm	Bottom	Y Displacement

Constraint Equation 2

0 = 1 (1/mm) * Top(X Displacement) + -1 (1/mm) * Bottom(X Displacement)

Coefficient	Units	Remote Point	DOF Selection
1	1/mm	Top	X Displacement
-1	1/mm	Bottom	X Displacement

Numerical Calculations

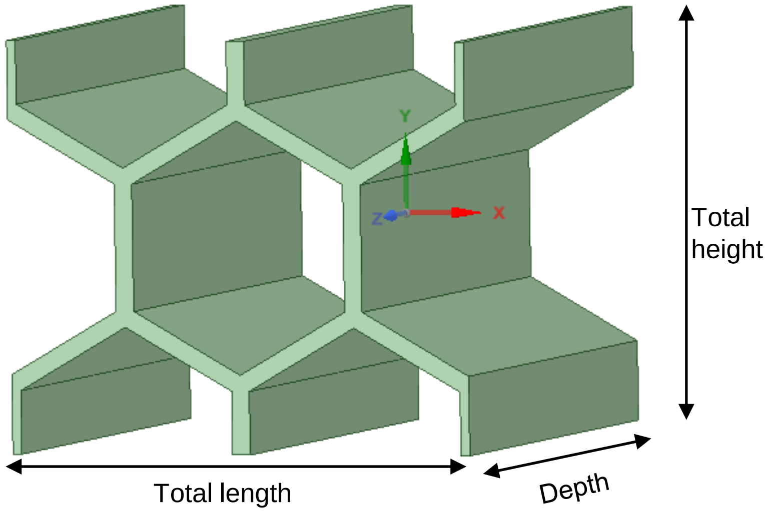
- To calculate the modulus of elasticity from ANSYS simulation, following calculations were performed –

- Equivalent area = total height * depth of cell
- Local Stress = Reaction force/Equivalent area (Reaction force is determined from ANSYS)
- Strain = total deformation/length of cell in x-direction (total deformation = 0.6 mm)
- Modulus of Elasticity = Local Stress/Strain

- Effective modulus [2] (in the next slides) was only calculated for the model without corner radius.

- For comparison, numerical calculations were performed for both the models.

- In this project, an isotropic material properties are used: Modulus of Elasticity = 1000 MPa, Poisson's ratio = 0.3, and density = 1000 $\frac{kg}{m^3}$ [5]



Dimensions of the Honeycomb cell

Mesh Size Analysis

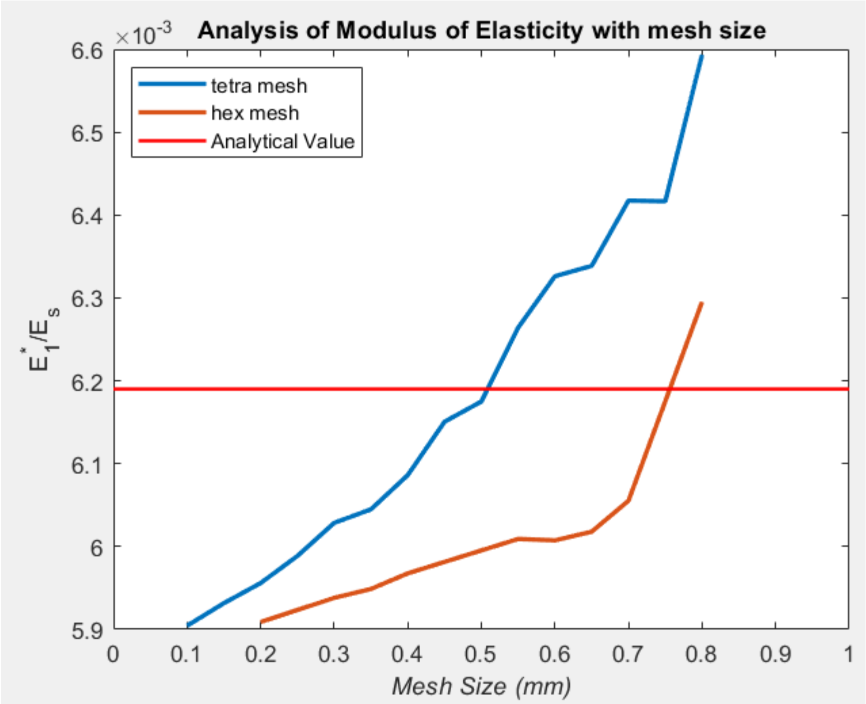
- Mesh size and type highly depends on the geometrical features like the thickness of honeycomb, it's depth, and it's length.

- Hex dominant meshing is generally preferred but due to the presence of corner radius (in actual model), I also analyzed tetrahedron mesh element with the quadratic order. Comparison for both the meshes with different size is below:

- Tetrahedron mesh was performed with adaptive mesh ON.

- Although the graphs are not converging, but considering all the limitations, I took the **mesh size of 0.3 mm for the tetrahedron elements**.

(Results for model with t = 1 mm, L = 6 mm, and depth = 30 mm)



Mesh Size Analysis

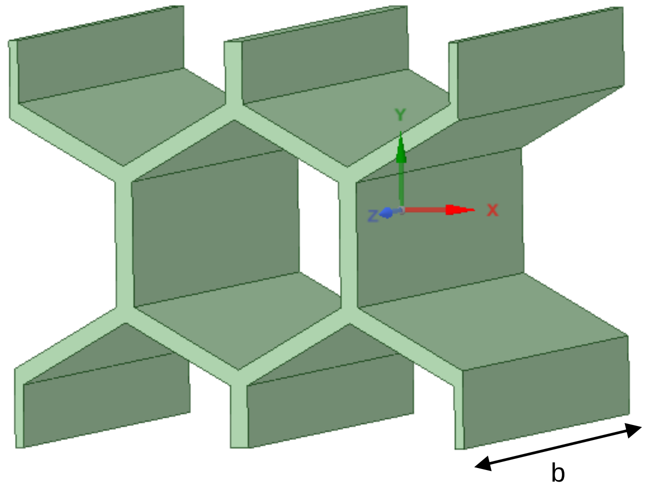
Honeycomb Depth Analysis

- The depth of the honeycomb cell in the out-of-plane (X_3) direction is very important to perform all the analyses as the results vary due to the variation in cell depth direction (Poisson's ratio) [4]

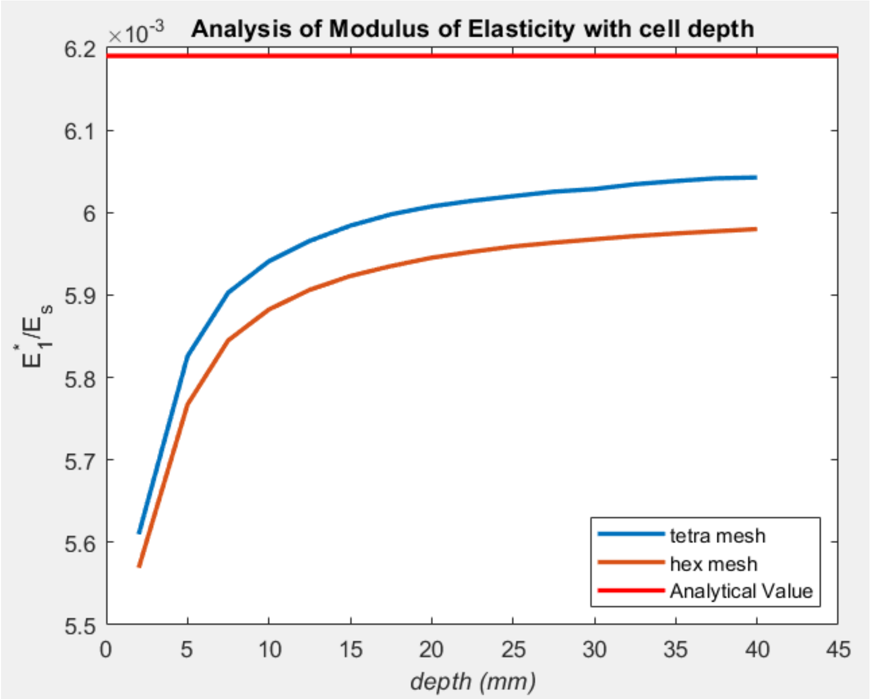
- To verify the mesh size consideration, depth analysis was performed with tetrahedron mesh size of 0.3 mm and hex dominant mesh size of 0.4 mm, comparison is below (for the model without corner radius):

- Based on the comparison and convergence, I considered the **cell depth as 30 mm** [5]**.**

(Results for model with
t = 1 mm and L = 6 mm)



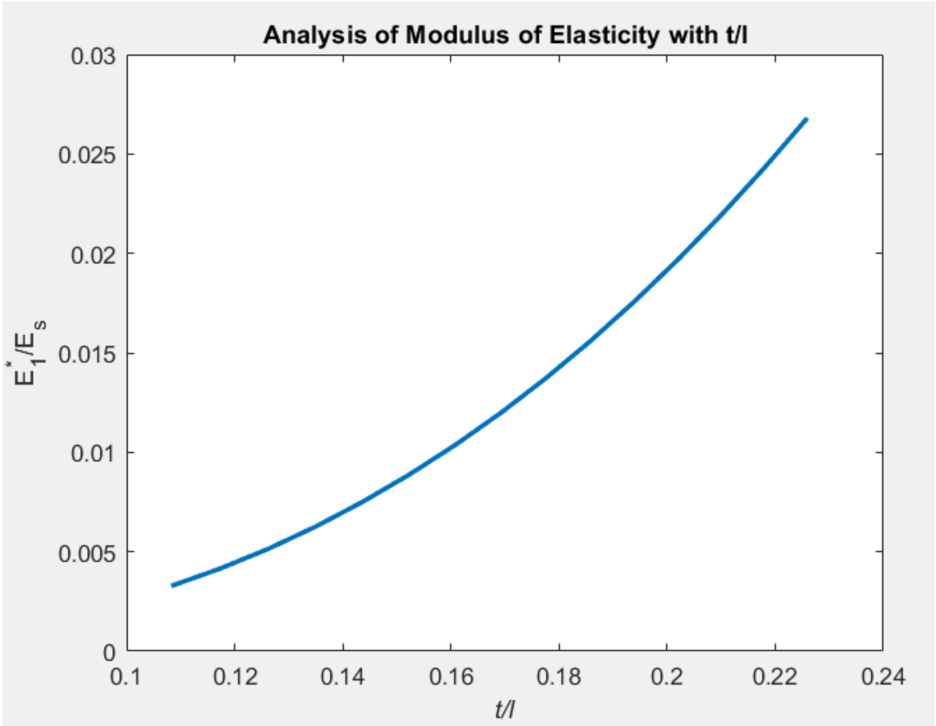
HC cell to represent its depth



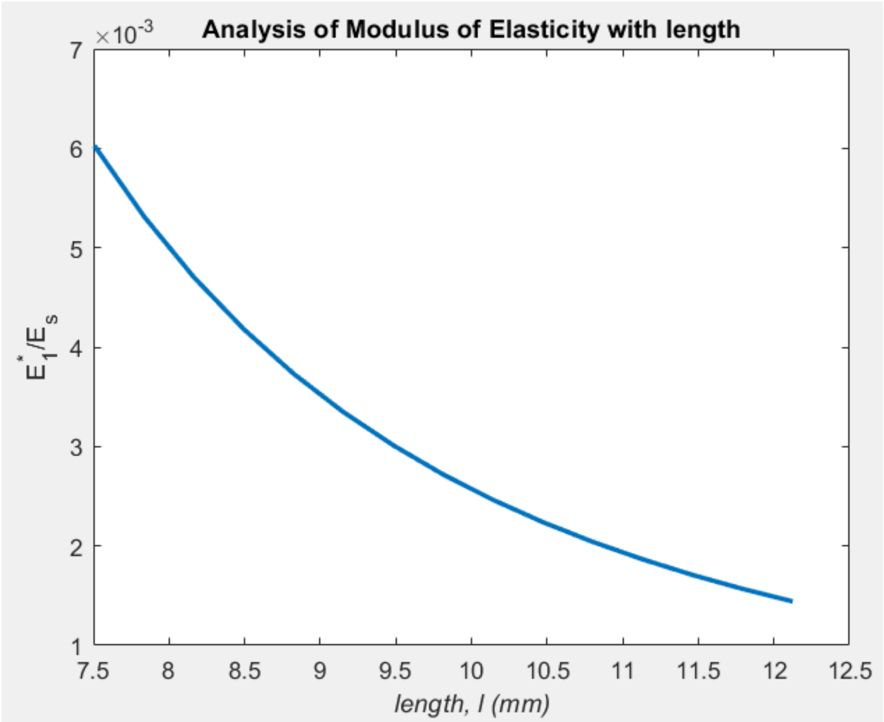
Cell Depth Analysis

3D Analysis (without corner radius)

- The model shown in the last slide was analyzed for a considered range of thickness and length and the following variations were observed:



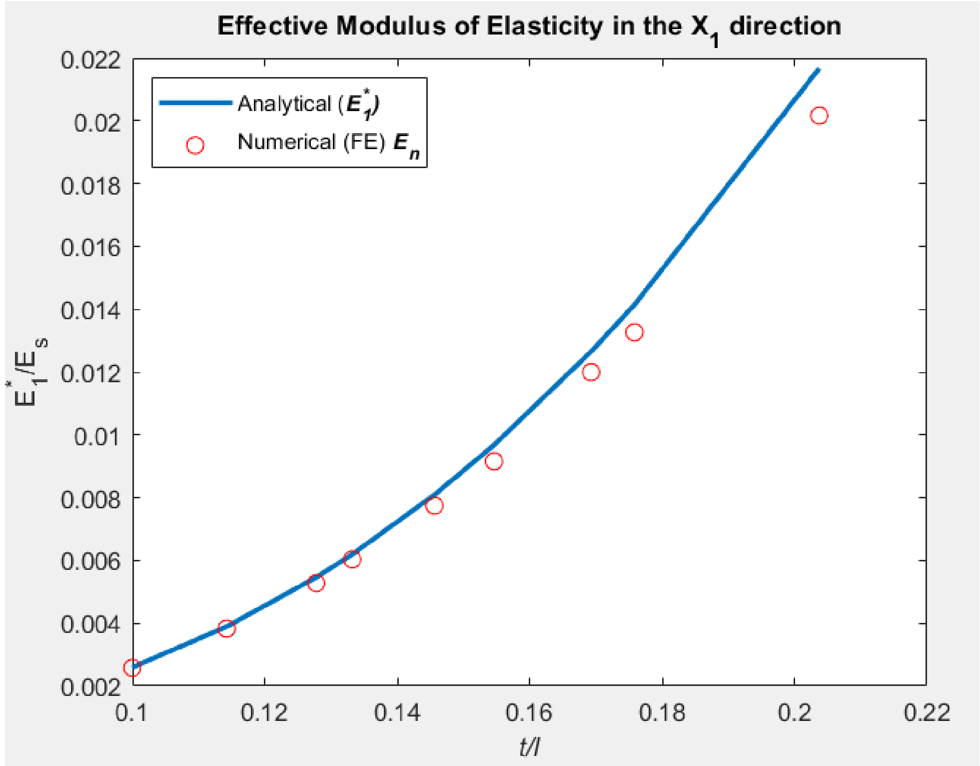
Variation of Young's moduli in X_1 direction with the ratio t/l



Variation of Young's moduli in X_1 direction with the length of cell

Resemblance with Literature

- To verify the simulation, all the results (including effective moduli using analytical equation) are plotted together and checked if they follow the trend showed in slide 6 :

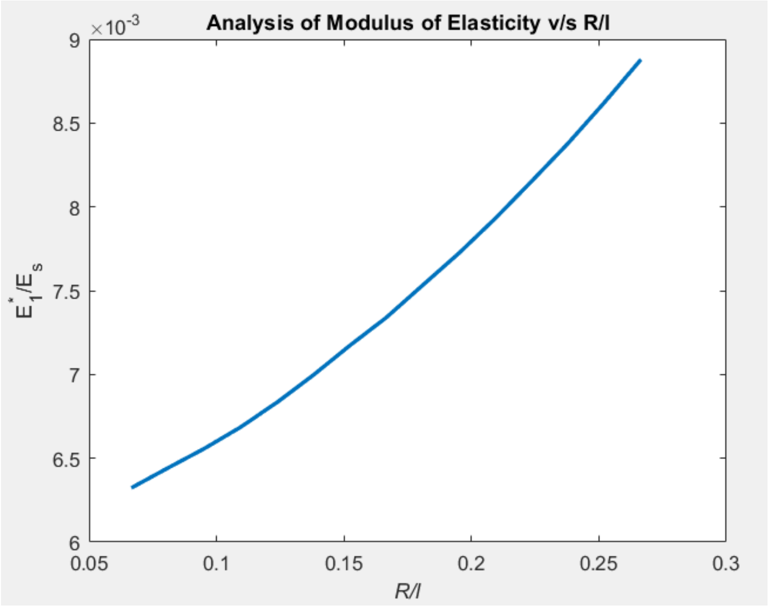


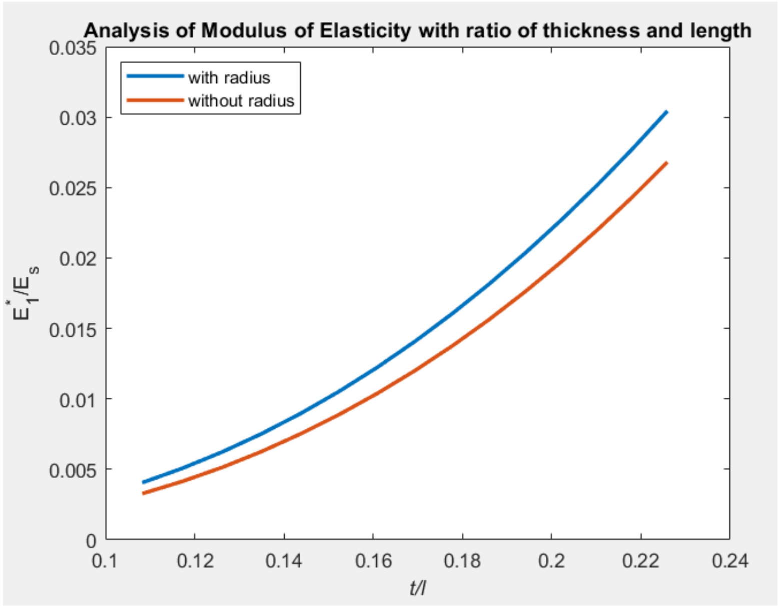
Comparison between analytical and numerical (FE) model

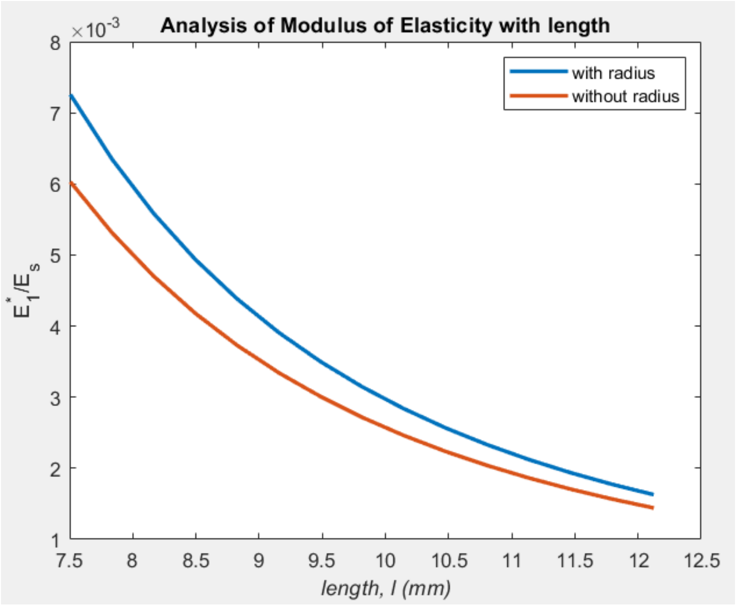
- The results resemble or follow the pattern showed previously and it verifies the boundary conditions.

3D Analysis (with corner radius)

- The model with the corner radius was analyzed and following variations were observed:







Variation of Young's modulus with corner radius (t = 1 mm, L = 6 mm, depth = 30 mm)

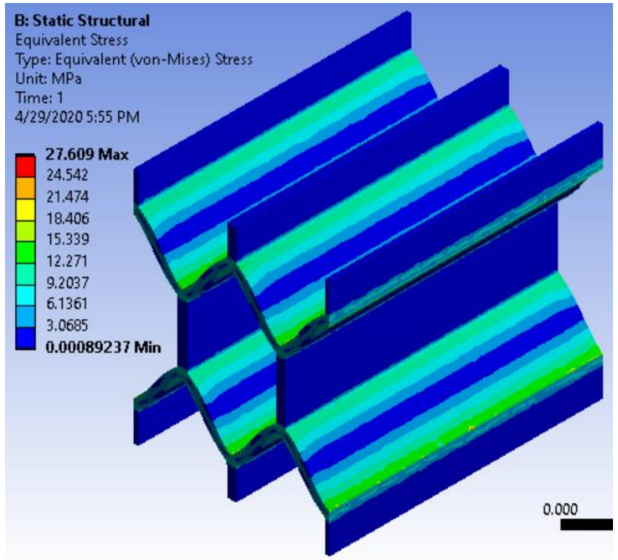
Comparison between with and without radius model for change in thickness and length (R= 1.2 mm, L = 6 mm, depth = 30 mm) (R= 1.2 mm, t = 1 mm, depth = 30 mm)

- It has been hypothesized that the corner radius increases the bending resistance and makes the material more stiff [8]. It can be verified from the above results as the moduli increases for the same geometry.

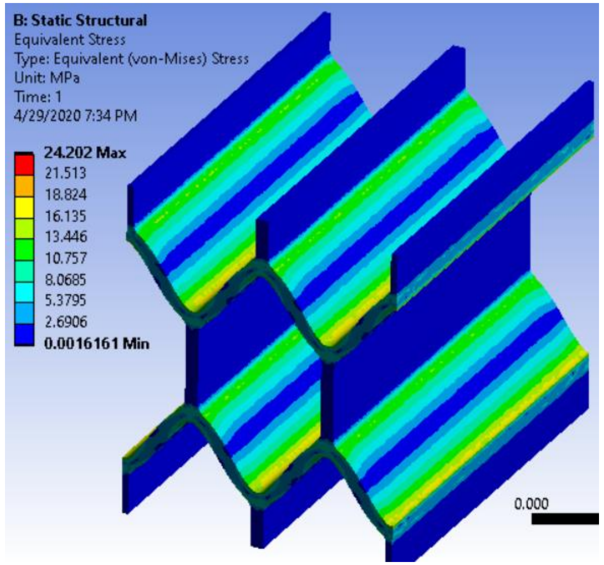
Stress Contour Plots

➢ Equivalent Stress plot for the models (t = 1 mm, L = 6 mm, and depth = 30 mm)

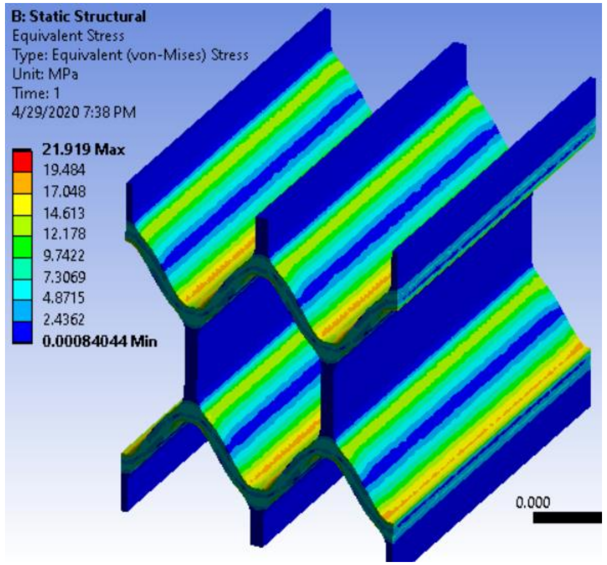
➢ Corner radius is a variable.



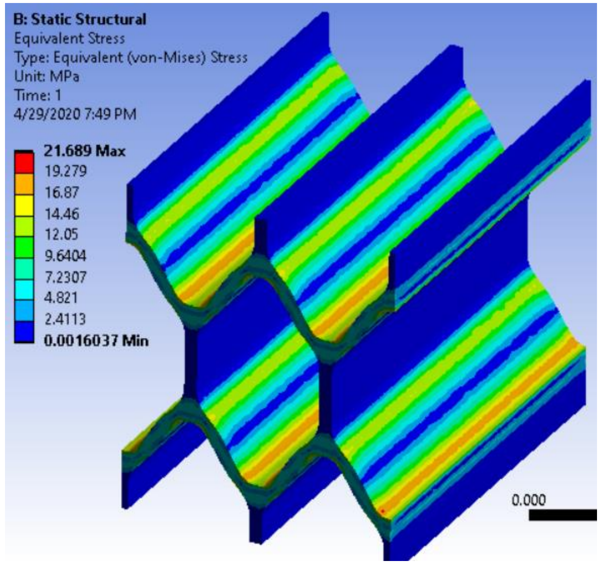
R = 0 mm



R = 1 mm



R = 2 mm



R = 2.5 mm

Stress Contours

➢ Stress concentration at the corners decreases with the increase in radius.

Parametrization of Output Parameters

- To perform the DOE, particular output variables needs to be parametrized. To get all the required results, following responses were parametrized in the ANSYS Mechanical:

  - Cell Volume

  - Force Reaction on the right faces (in the negative direction)

  - Equivalent von-Mises Stress

Outline

Value Selection and DOE Method

- To perform design of experiments, following values of all three parameters were selected:

Levels	Thickness, t (mm)	Length, L (mm)	Radius, R (mm)
Low	1	6	1.2
Medium 1	1.2	6.72	1.4
Medium 2	1.4	7.44	1.6
High	1.6	8.16	1.8

- The low and high values for length and thickness were taken and calculated from the research work [4,5]. The medium value were calculated by dividing the range into equal (three) interval.

- From [5], the value of corner radius depends on the method of fabrication and it generally lies between (0.1-0.4) times length of hexagon.

- A **full-factorial design** method with 64 design points was used to perform the DOE in ANSYS and results were evaluated.

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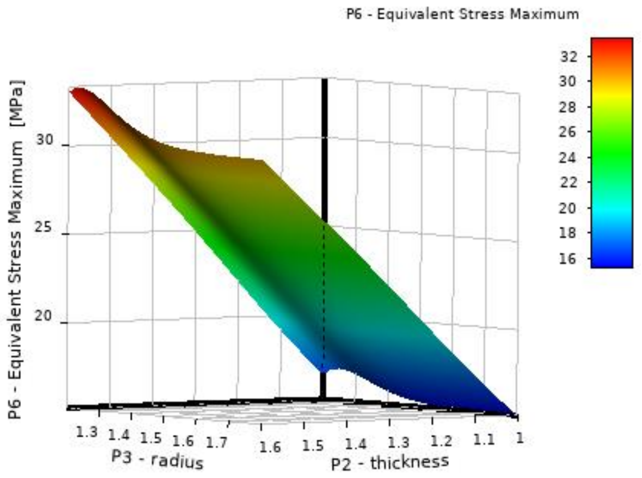
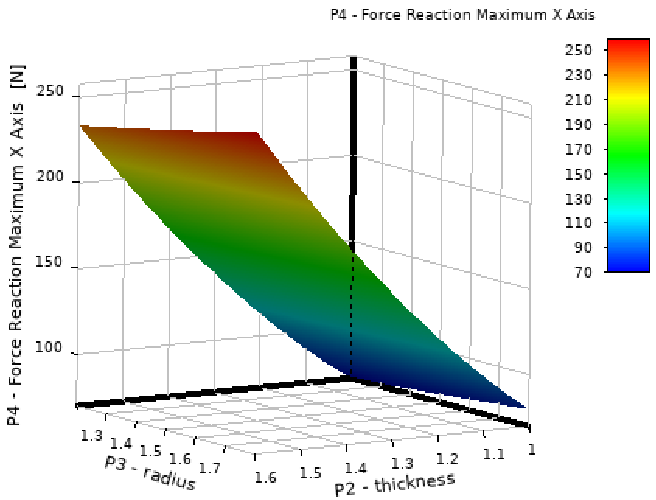
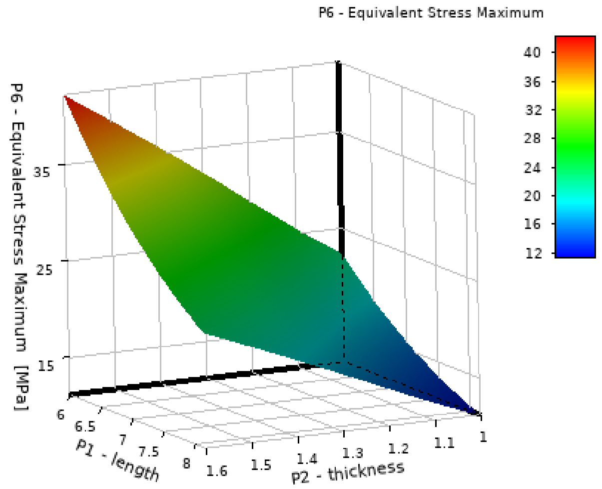
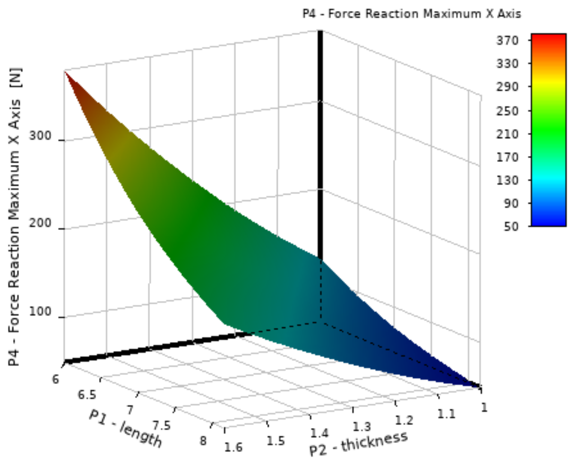
Response Surface Methodology

- To make the response surface between parameters, standard response surface method – full 2^{nd} order polynomial method was used [7]



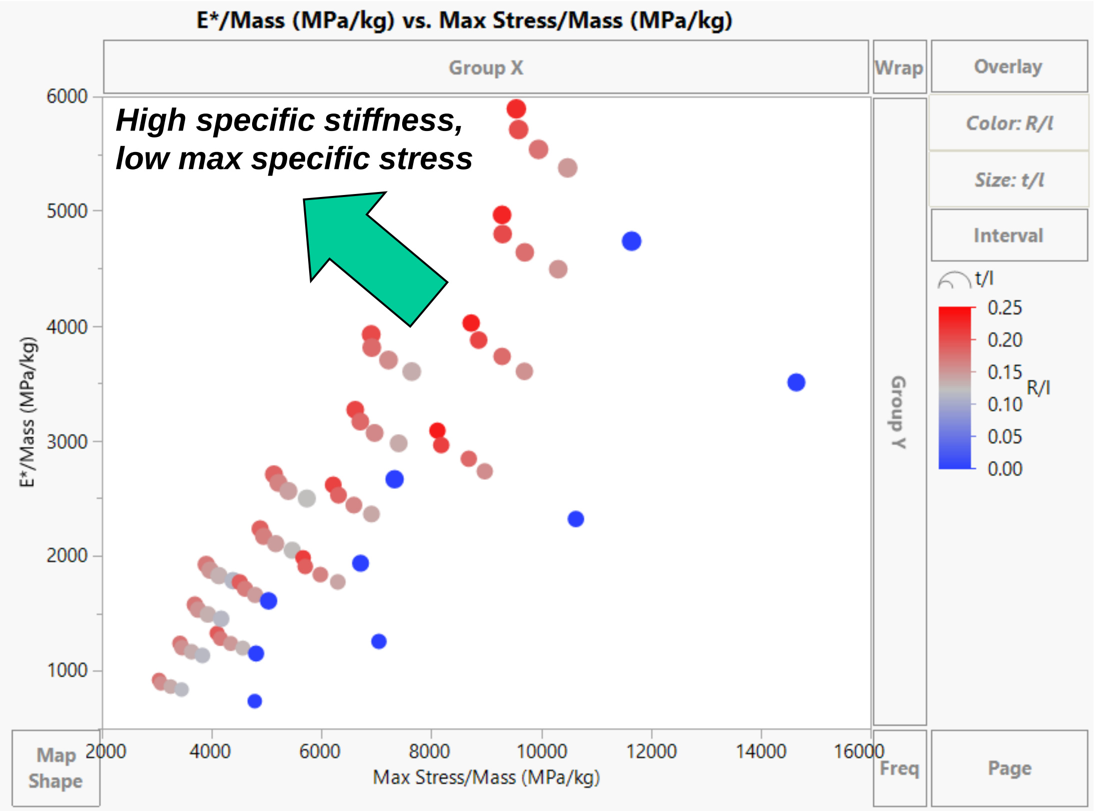






Multi-Objective Graph

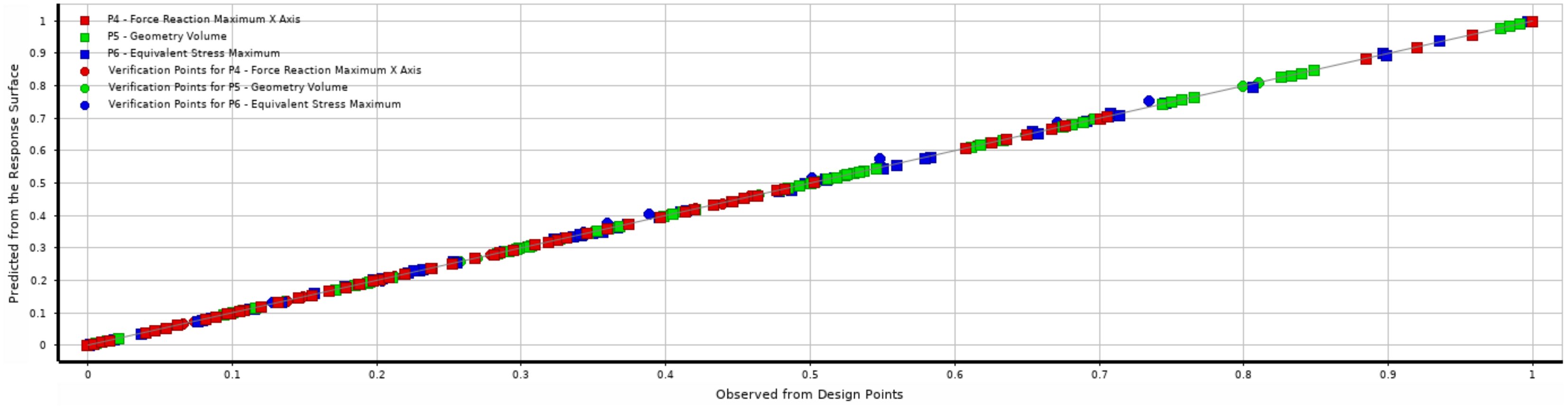
➢ Following graph between specific stiffness and specific stress was plotted in JMP.



Specific stiffness and specific stress for varying R/l and t/l

Verification and Goodness of Fit

- To verify the results from the response surface, six verification plots were analyzed other than the design points and goodness of fit was observed.



Goodness of Fit

- Three-star rating in ANSYS shows a good fit on the response surface.

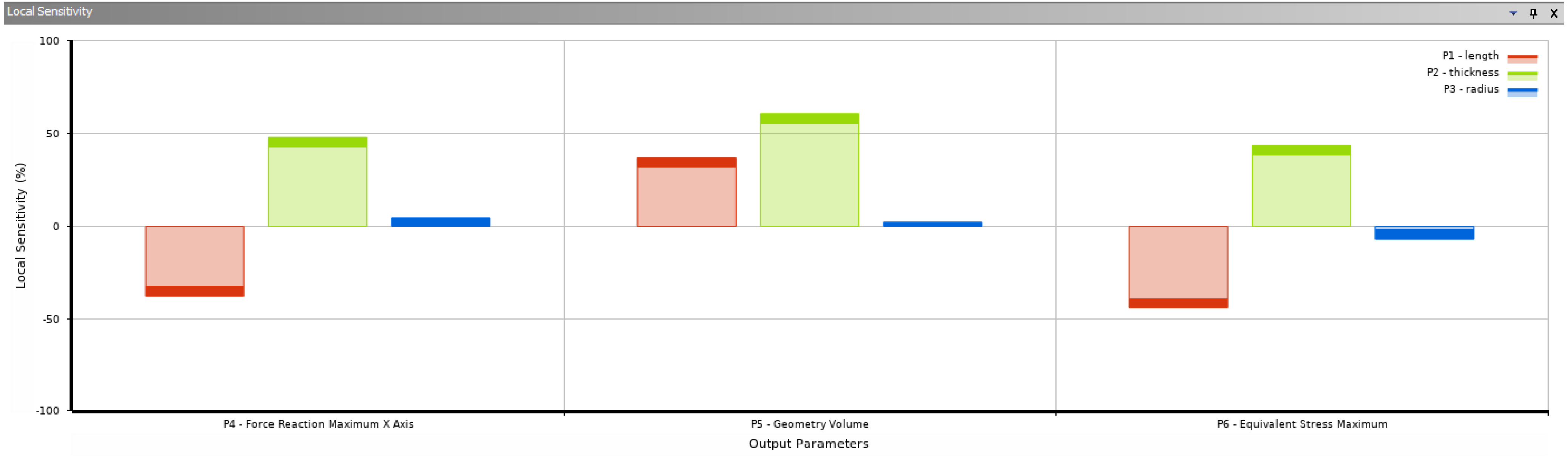
Table of Schematic C3: Response Surface

	A	B	C	D
1		P4 - Force Reaction Maximum X Axis	P5 - Geometry Volume	P6 - Equivalent Stress Maximum
2	Coefficient of Determination (Best Value = 1)			
3	Learning Points	1	1	0.99983
4	Root Mean Square Error (Best Value = 0)			
5	Learning Points	0.14238	4.399E-12	0.10815
6	Verification Points	0.35257	4.7108E-12	0.42788
7	Relative Maximum Absolute Error (Best Value = 0%)			
8	Learning Points	0.43445	0	3.8805
9	Verification Points	0.74866	0	× 11.343
10	Relative Average Absolute Error (Best Value = 0%)			
11	Learning Points	0.12584	0	0.99084
12	Verification Points	0.32344	0	4.2557

Response Surface Verification

Sensitivity Analysis

- Following figure shows the sensitivity of output parameters with the variation in the input parameters.



Sensitivity Analysis

Outline

Optimization Method and the Objective

- The objective of this project is to optimize the honeycomb parameters such that it has least volume with a good sufficient safety factor.

- Here, the constraint was set to be the value of maximum equivalent stress (von-Mises) to be less than 15 MPa and the volume of cell was optimized.

- The initial values were taken as the medium level values to start the process of optimization.

- The method of optimization was considered as NLPQL (Nonlinear Programming by Quadratic Lagrangian)

- Three candidate points were determined for the optimized value.

	A	B	C	D	E	F	G
1	Name	Parameter	Objective		Constraint		
2			Type	Target	Type	Lower Bound	Upper Bound
3	Minimize P5	P5 - Geometry Volume	Minimize		No Constraint		
4	P6 <= 15 MPa	P6 - Equivalent Stress Maximum	No Objective		Values <= Upper Bound		15

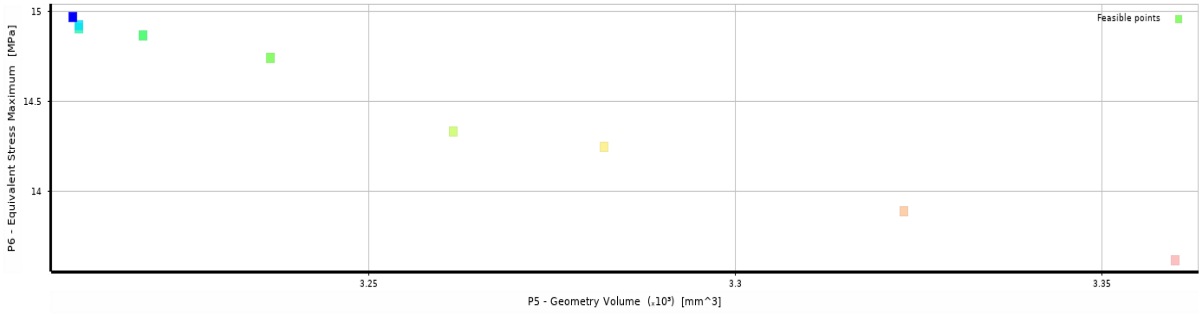
Table of Optimization

Convergence and Candidate Points

➢ Following results were obtained for the optimization:

	A	B	C	D	E
1	⊟ Optimization Study				
2	Minimize P5	Goal, Minimize P5 (Default importance)			
3	P6 <= 15 MPa	Strict Constraint, P6 values less than or equals to 15 MPa (Default importance)			
4	⊟ Optimization Method				
5	NLPQL	The NLPQL method (Nonlinear Programming by Quadratic Lagrangian) is a gradient-based algorithm to provide a refined, local, optimization result. It supports a single objective, multiple constraints and is limited to continuous parameters. The starting point must be specified to determine the region of the design space to explore.			
6	Configuration	Approximate derivatives by Forward difference and find 3 candidates in a maximum of 25 iterations.			
7	Status	Converged after 58 evaluations.			
8	⊟ Candidate Points				
9		Starting Point	Candidate Point 1	Candidate Point 2	Candidate Point 3
10	P1 - length	7.08	7.2996	7.3673	7.4273
11	P2 - thickness	1.3	1	1	1
12	P3 - radius	1.5	1.3592	1.3478	1.348
13	P5 - Geometry Volume (mm^3)	4088.7	3209.8	3236.7	3261.7
14	P6 - Equivalent Stress Maximum (MPa)	23.16	14.967	14.74	14.331

Candidate Point Results



Feasible Point Plot

➢ Candidate point 3 shows the less stress but candidate point 1 gives the least volume for the stress to be less than 15 MPa.

Optimized Values and Verification

- After performing optimization, the values of input parameters for the set objective are given as:

Parameter	Value
Length (mm)	7.30
Thickness (mm)	1
Radius (mm)	1.36
Cell Volume mm^3	3209.8
Maximum Equivalent Stress (MPa)	14.967

- The model is again analyzed at the optimized values to see the variation from the Optimization results and the following results were obtained:

Cell Volume mm^3	3209.8
Maximum Equivalent Stress (MPa)	14.967

- It can be observed that the results are equal (generally, they are very close) and the optimization results can be verified.

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  - Designing in SpaceClaim
  - Parametrization of Input Parameters
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  - Mesh Size Analysis
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Conclusion

- The purpose of this work was to optimize the honeycomb cell parameters such that the maximum equivalent stress is well under the safe limit and understand the effect of corner radius on the mechanical properties of the honeycomb cell.

- The model without the corner radius was analyzed and the boundary conditions were verified through the resemblance of results available in the past research work in [2].

- The model with corner radius was assumed to be more stiff and it was verified for the various values of input parameters.

- Finally, the model was optimized by using full-factorial DOE method, standard response surface method, and NLPQL optimization method.

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Future Work

- Other mechanical properties like tension and shear variables can be analyzed in both the in-plane directions and the out-of-plane direction by considering the corner radius.
- Results of the corner radius can be verified in the coming future by developing the analytical equations for the calculation of properties like effective moduli or density.
- Study the effect of corner radius on the stress concentration when the radius is large.
- Other conditions like thermal properties can be implemented on the boundaries/walls of the cell and the variations in the results can be analyzed.
- Process of optimization can be used to design improved multi-functional honeycomb panels

Outline

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Thank you

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