DESIGN AND DEVELOPMENT OF DAMPED BORING BAR USING CELLULAR SOLIDS

Batch 3

STUDENT DETAILS	
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Problem definition

- A large length to diameter ratio - vibration(chatter) often occurs and it leads to a negative impact on the processing quality and processing performance

- Damping is a way to limit vibrations and is essential for protecting the system in which it operates at high speeds

- To improve machining performance of the tool by eliminating vibration

Objective

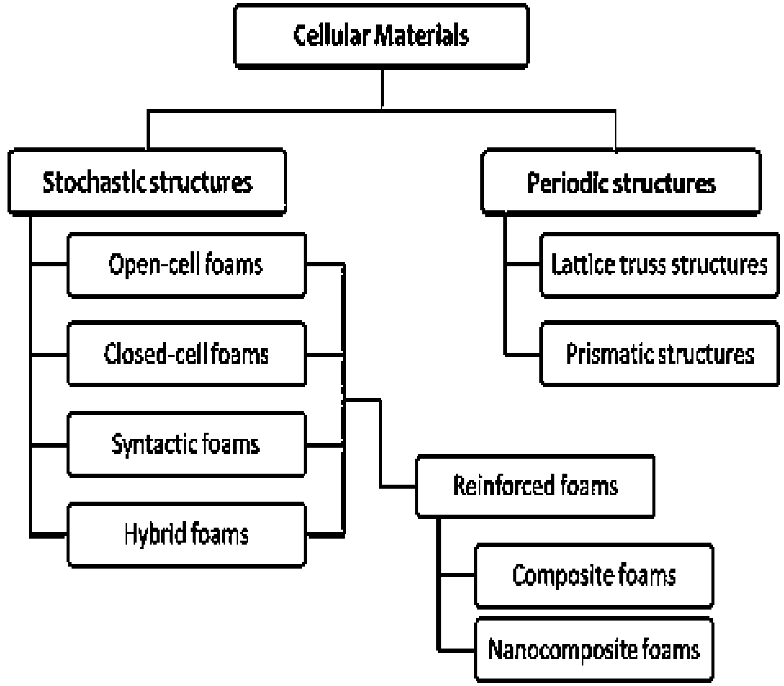
- To design and develop a high damped cellular structure boring bar instead of conventional solid bar to improve the dynamic stability of the boring tool to bore smaller diameter holes

Literature survey

Classification of Cellular Materials

❑ Duarte, N. Peixinho et al., 2019

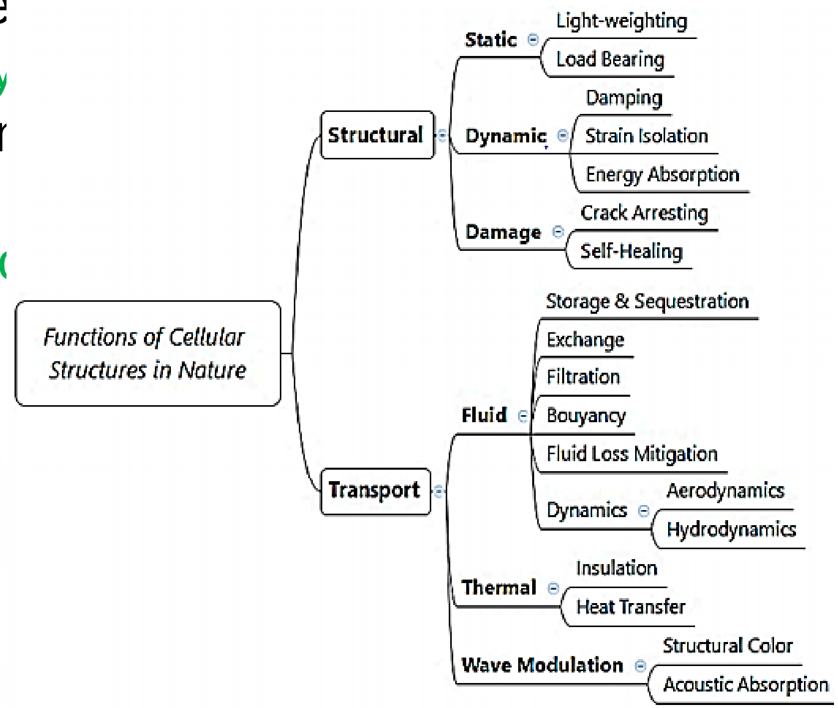
- Based on the base material, these materials are grouped into cellular metals, cellular ceramics and cellular polymers
- Stochastic structure are porous and it has high energy absorbing capacity
- Open cell structure – High surface area
- Closed cell structure has high structural efficiency, and damping



Classification and selection of cellular material in mechanical design

❑ Dhruv bhate et al., 2019

- Cellular material is classified in three leve' – Tessellation, Element type , Connectivity
- Biomimetic approach is used in selectior of cellular structure
- Toucan beak structure – high dynami stiffness , Closed cell foam structure



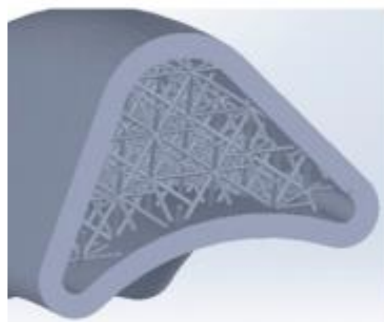


Fig.1 Toucan beak structure

Cellular Materials characteristics

The Mechanical Properties of Cellular Solids

- **M.F. ASHBY R et al., 1998**
  - Mechanics of natural materials such as wood, corks, bones etc.,
  - Cellular solids – simultaneous optimization of **strength, stiffness , weight**
  - Cellular solids – foundation for designing with foams for **load bearing structure**
  - Foam filled sandwich structure gives **longitudinal** and **flexural stiffness**

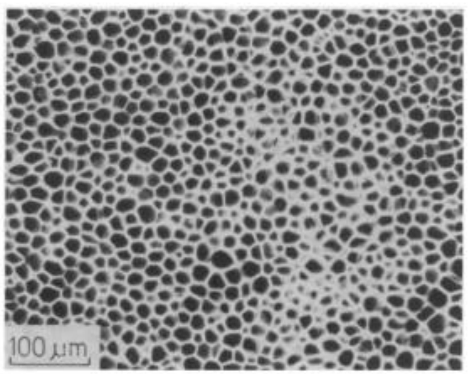


Fig.2 Cells in cork

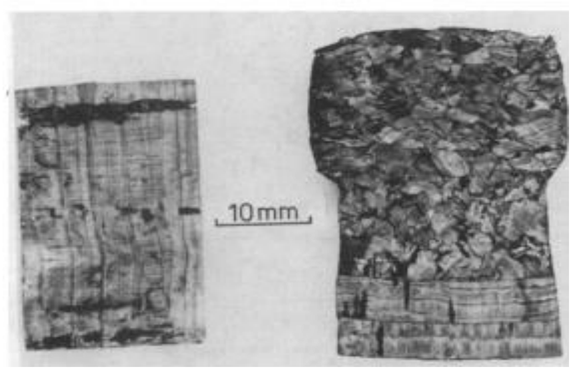


Fig. 3 Sections through corks.
(Axis of symmetry of the cork structure)

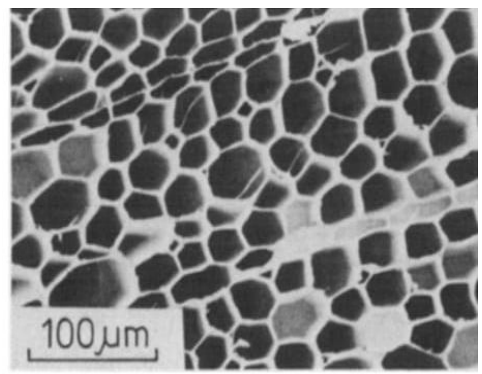


Fig.4 Sandwich structure in wood

❑ F- J. Ulm et al., 2001

- Mechanical behaviour of cellular solids – linear elastic ,cell wall buckle , densification
- Increased **moment of inertia** in sandwich panel – efficient **bending** and **buckling stiffness**
- Combinations of face and core materials are used;
  - Faces - steel, aluminum, or wafer board
  - Cores - foamed polyurethane, foamed polystyrene bead board, or foamed glass
- Sandwich panel – **economic material**

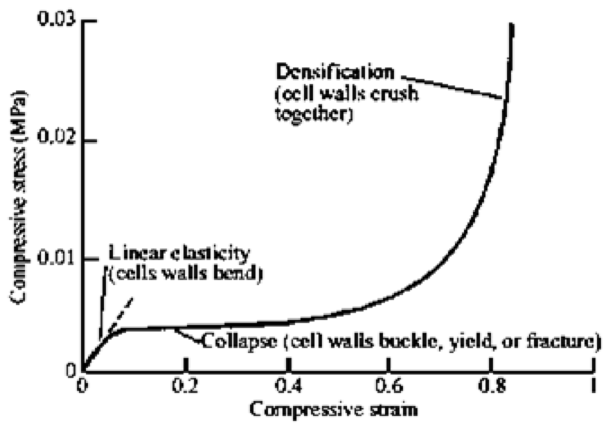


Fig.5 Stress strain curve for cellular solids

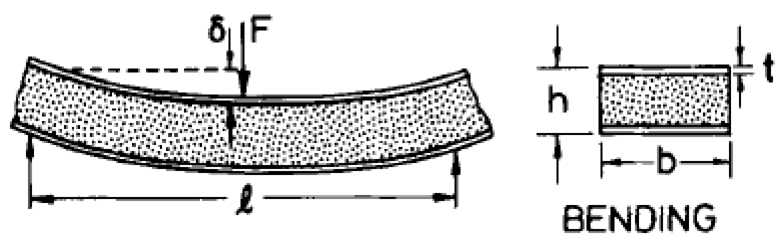


Fig.6 Bending in sandwich panel

How cellular structure absorbs energy ?

Gibson et.al , cellular solids,

- Energy absorbing capacity of cellular solids is **higher** than dense solids
- Cell wall buckles **up to densification** , so energy is absorbed up to densification
- Using **elastomeric** material provides **linear elastic buckling** of cell wall
- Increase in **relative density** reduces the **elastic buckling range**

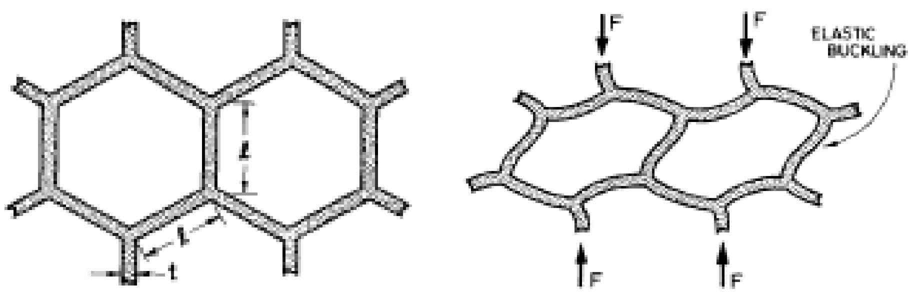


Fig.7 Elastic buckling of honeycombs

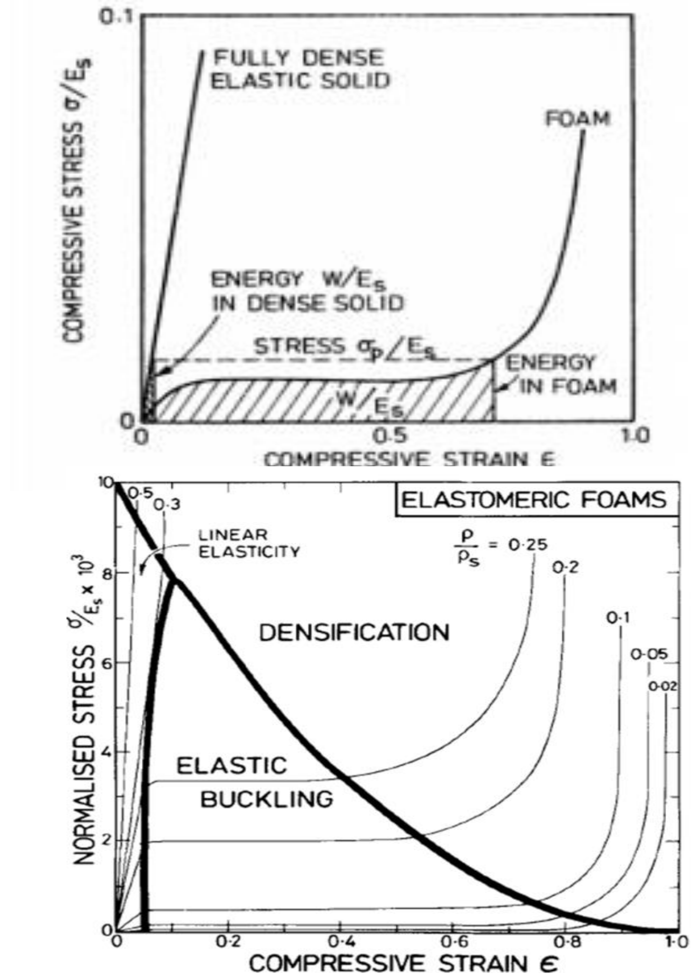


Fig.8 Energy absorption curve
Source : Gibson et.al , cellular solids

Numerical inverse engineering as a route to determine the dynamic mechanical properties of metallic cellular solids

- **V.H. Carneiro et al., 2020**

- Direct experimental approaches on low damping cellular solids tends to be tampered by external damping sources, an indirect numerical inverse engineering approach is presented as a solution
- Numerical inverse engineering is carried on Al based stochastic structure to determine damping ratio

Fig.9 3D-printed model

Fig.10 Experimental setup for vibration testing

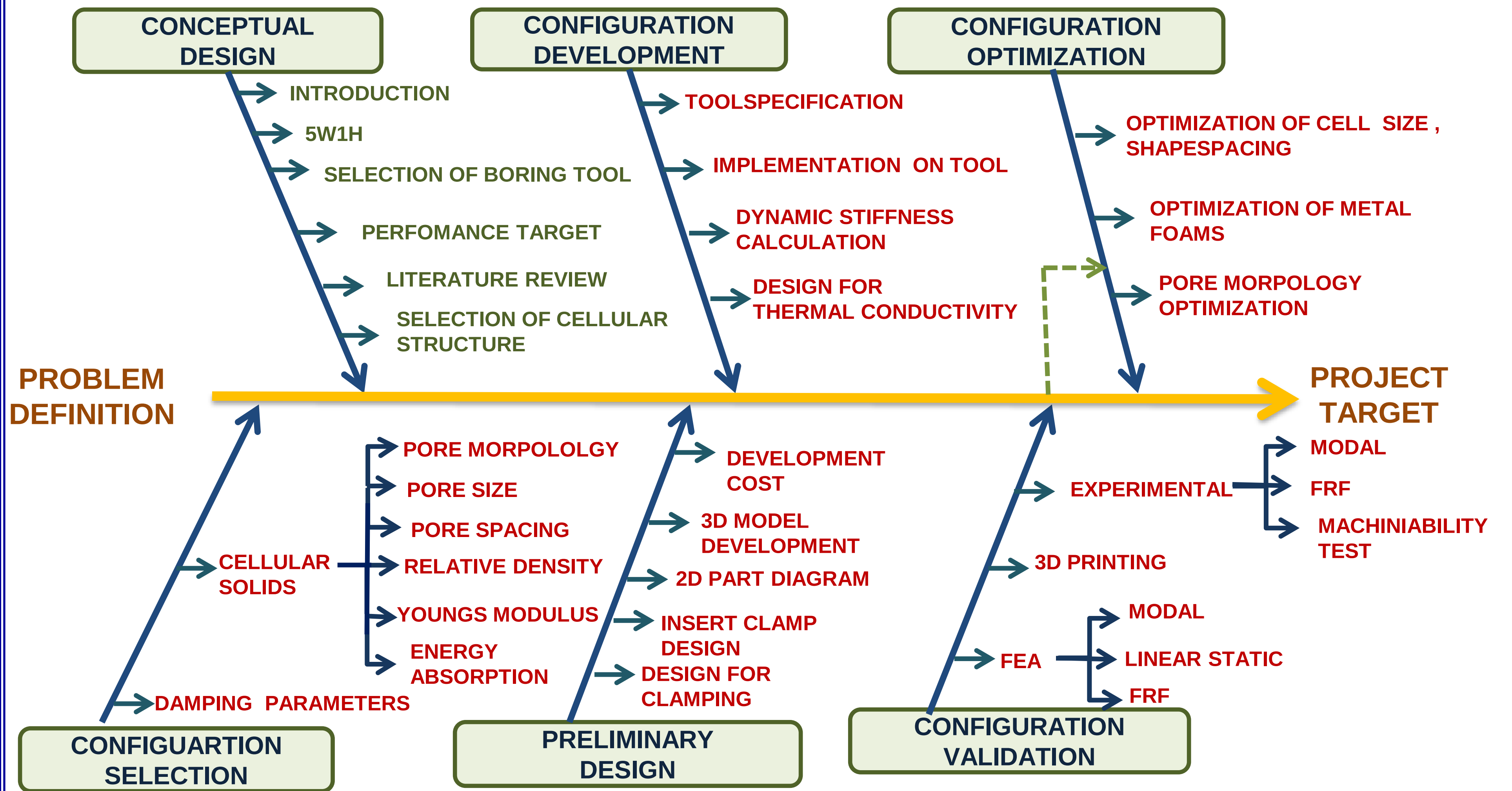
Summary

- Sandwich structure has high longitudinal and bending stiffness
- Stochastic structure has high energy absorbing capacity
  - Closed cell structure has better damping
- Numerical inverse engineering is used for determining damping ratio

Gaps in literature

- Cellular solids is not implemented in boring tool
- Very few studies on FEA of closed cell structure

Fish bone analysis



Preface

- A **large length to diameter ratio** - vibration(chatter) often occurs and it leads to a **negative impact on the processing quality** and processing performance
- Implementation of **alternate material** over conventional material to enhance damping property
- Improving **dynamic stiffness** of system improves **vibrostability**

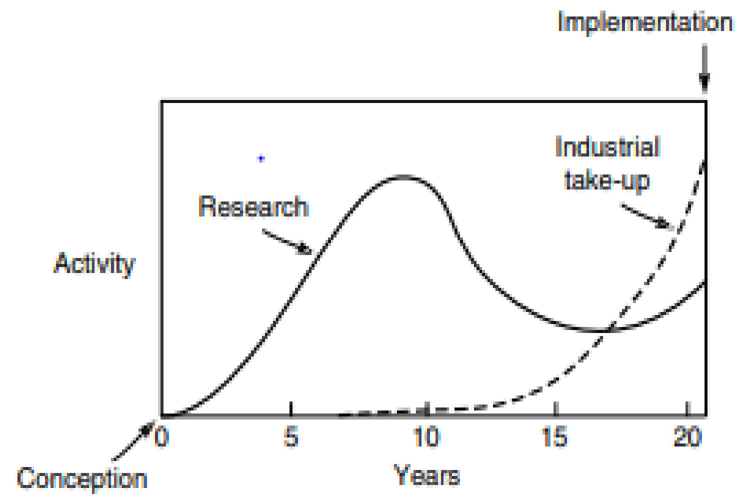


Fig.11 A development history typical of many new material

Source: ASHBY R et al, Metal foams : A design guide M.F.., 2000

Why we need to improve the dynamic stiffness of the boring bar ?

Improved dynamic stiffness in the Boring bar offers

- Chatter free operation
- Increases unconditional stable region
- *Natural frequency* of the system *increases*
- *Overhang length* of tool can be *increased*
- Significant improvement in productivity and better surface quality

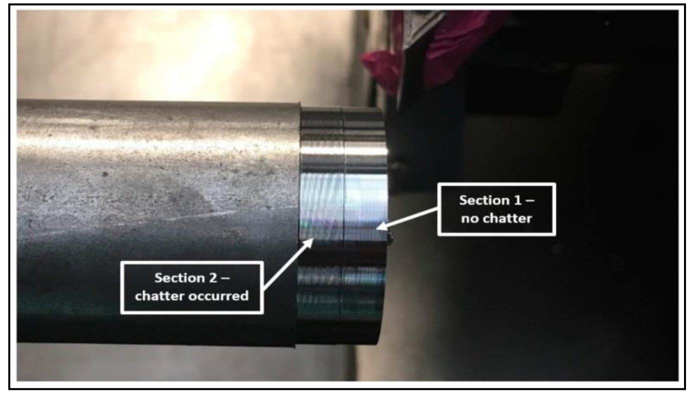


Fig. 12 Machined surface of chatter tool

Source: Jasiewicz M et al., Implementation of an algorithm to prevent chatter vibration in a CNC system materials. 2019

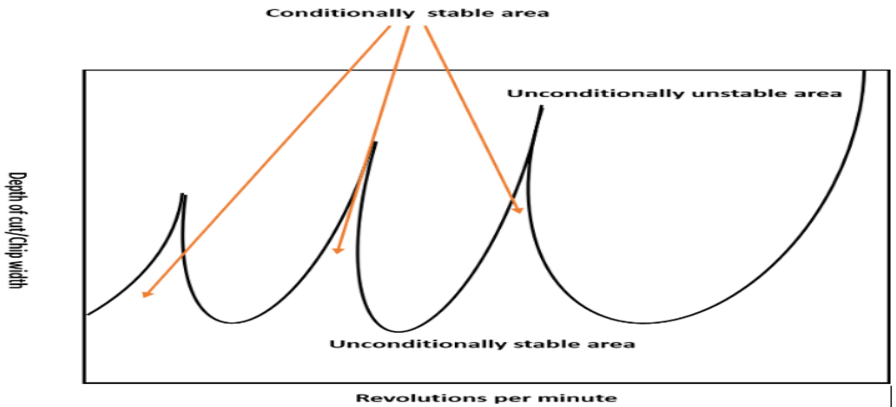


Fig.13 Stability lobe diagram

Source: Mfg Tech update, Chatter in milling

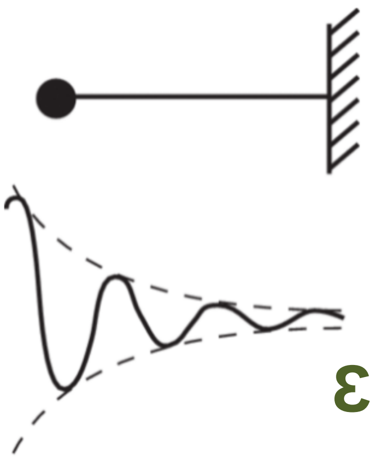
How to Improve dynamic stiffness ?

Dynamic stiffness ← $D = \varepsilon * K$ ---- 1

ε → Damping ratio

K → Static stiffness

Factors influencing…



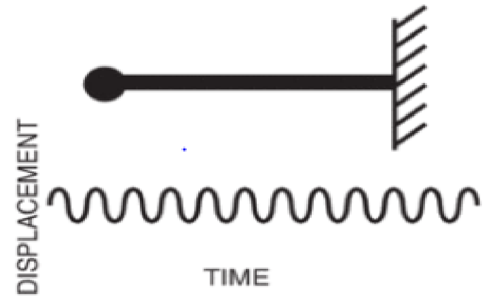
Damping Ratio (Material)

- Mass
- Stiffness

$$\varepsilon = \frac{c}{2\sqrt{mk}} \quad \text{---- 2}$$

Static stiffness

- Clamping method
- Over hang length
- Young's modulus
- Moment of inertia



$$n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad \text{---- 3}$$

*'Natural frequency of the system depends **mass** and **stiffness**"*

5W1H

WHAT?
To design and develop a damped boring bar

WHY ?
A large length to diameter ratio - vibration(chatter) often occurs and it leads to a negative impact on the processing quality and processing performance, damping is a way to limit

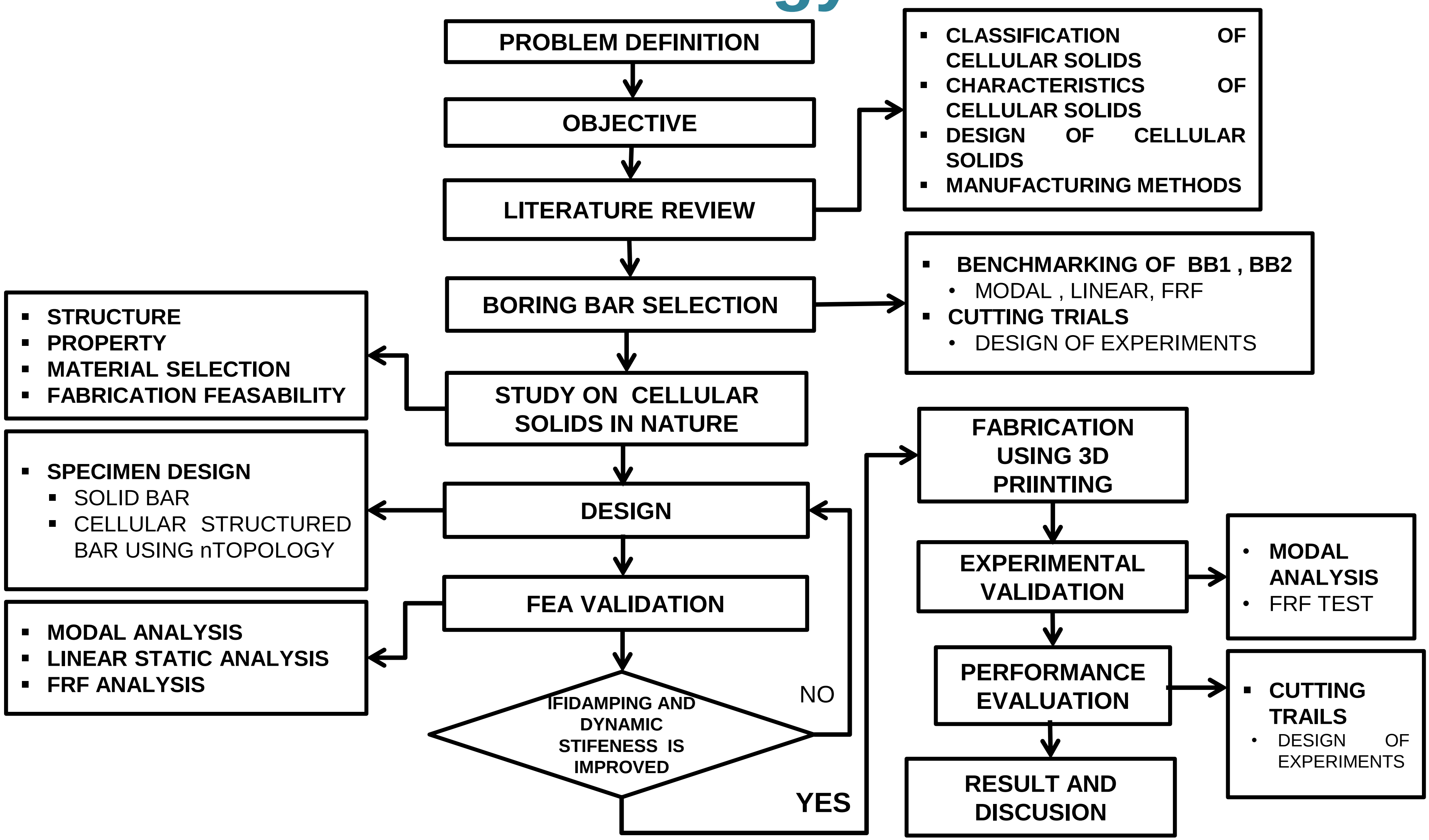
HOW?
1. Benchmark from existing boring bar project
   - Experimental work
     - Modal-Natural frequency, damping ratio,
     - FRF- stability/dynamic stiffness
2. Studies on characteristics and parameter of cellular solids
   - Static and dynamic properties
     - Material – alloy type
   - Topology-shape
   - Cell geometry-size
3. Design of solid and cellular structure bar using creo Parametric
4. Fabrication of designed solid bar and cellular structured bar by using metal additives - 3D printing
5. Testing-Experimental validation
   - Static, Modal, FRF
6. Development of FEA model for solid bar and cellular structure bar using nTopology
7. Implementing developed methodology for damped boring bar

WHO?
- 1, Project team 2020-PSG CT
- 2,3, Project team 2021-PSG CT
- 4, Manufacturing by 3D printing centre- IIT Palakkad
- 5-7, Project team 2021-PSG CT

WHERE?
- Specimen design and analysis
  - Department of Mechanical Engineering, PSG CT
- Specimen manufacturing
  - 3D Printing Centre, Metal additive manufacturing lab , IIT Palakkad
- Static condition test
  - PSG INDU TECH computerized UTM
- Vibration test
  - PSG Machine Tool Centre

WHEN?
- Phase I
  - 1, June 2020-April 2021
  - 2, July 2nd week to August 3rd week
  - 3, August 4th week to September 3rd week
  - 4, September 4th week to October 1st week
  - 5,6, October 2nd week to November 1st week

Methodology



Why to improve damping in boring bar?

Problem definition

- Vibration is often the **limiting parameter** in gaining high output in the machine i.e. speed , feed and depth of cut
- Damping is a way to **limit vibrations** and is essential for protecting the system in which it operates at high speeds
- Damped boring bar **reduces cost of operation**

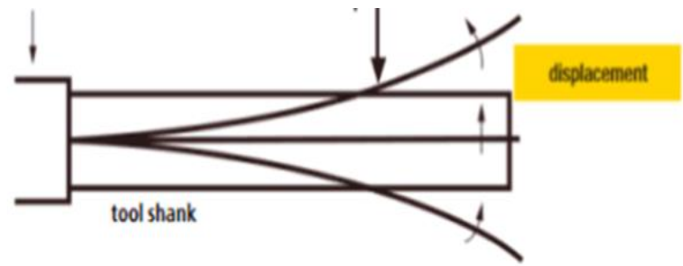


Fig.14 Chatter in boring bar
Source : Kennametal

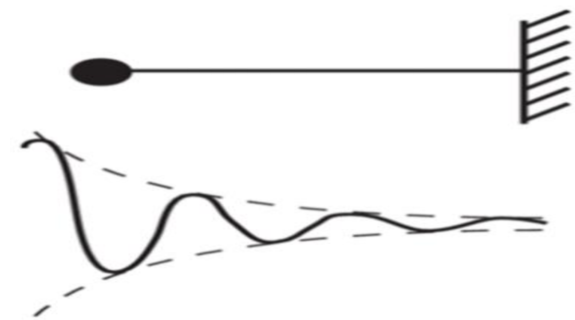


Fig.15 Damping in cantilever beam
Source : *Kip Hanson et al. 2020,boring tool sme*

What is damping in boring bar?

Objective

- Damping is the **dissipation of vibratory energy** in solid mediums and structures over **time and distance**

- To design and develop a high damped **cellular structure** boring bar instead of conventional **solid bar** to improve the dynamic stability of the boring tool to bore smaller diameter holes

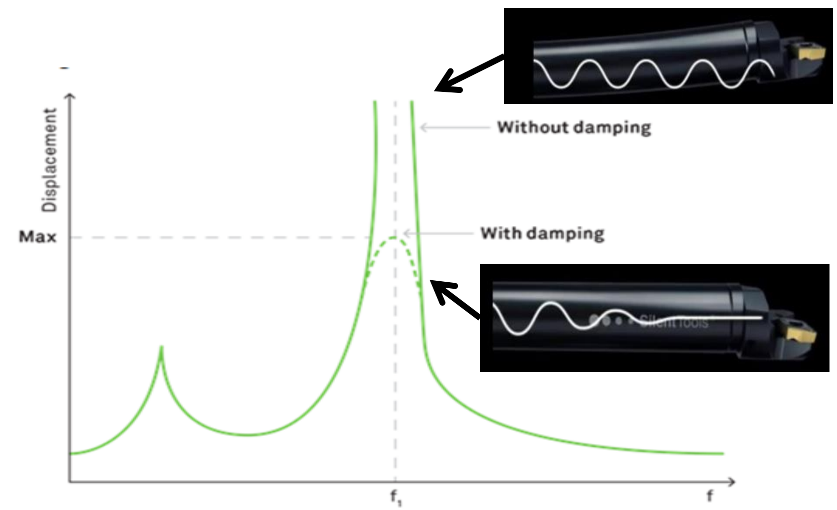


Fig.16 Frequency response plot

Source : *ACC ,Why damping is important for construction ?*

Where we use damped boring bar?

The damped boring bars are used for manufacturing

- Machining **small diameter holes**
- Superior quality and highly accurate **industrial automation equipment**
- Automotive parts
- Medical implant accessories
- **Thin walled** aerospace parts
- IC engines, hydraulic cylinders

Fig.17 Thin wall machining

Fig.18 Engine block machining

Fig.19 Machining medical implants

Source **:** New engineering practice BlogSpot

When damped boring bars are used?

- Large length to diameter ratio is required for machining
- **High material removal rate** is required
- When **surface quality** of machining is required to be improved by increasing the
  - ✓ Natural frequency
  - ✓ Static stiffness
  - ✓ Damping ratio
- **Low operating cost** is required

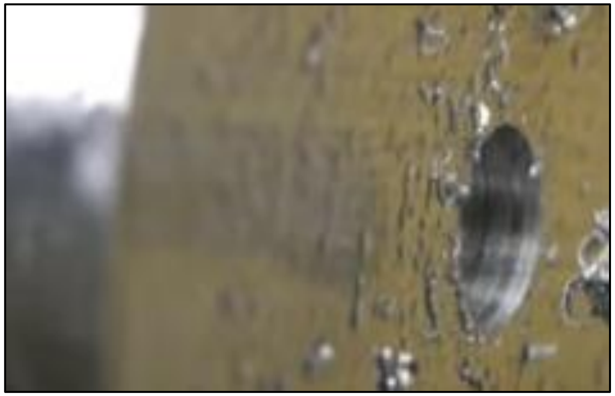


Fig.20 Conventional boring bar

Fig.21 Damped boring bar

Source : Canstockphoto

Who are beneficiaries ?

- Manufacturing company who requires **close tolerance** with long overhang
- **Aerospace** and **medical** equipment manufacturer
- Small scale companies aiming for low production cost

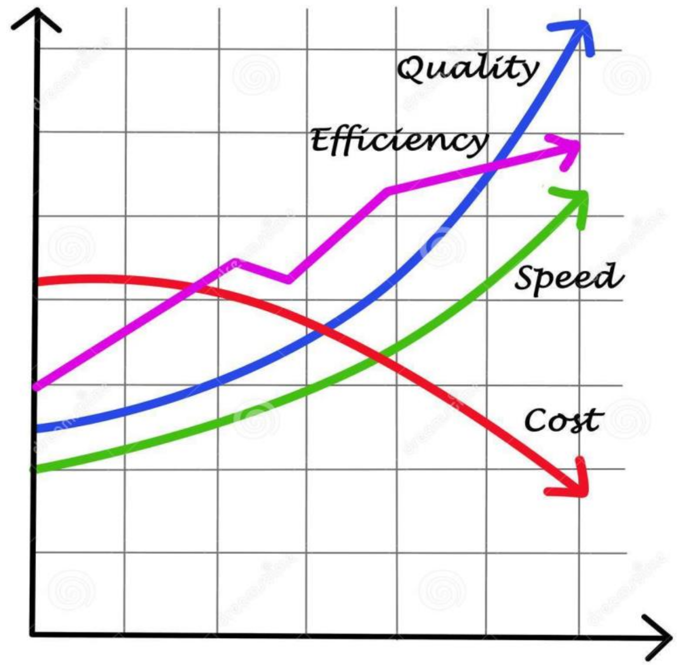


Fig.22 Quality vs cost graph

Source : Colonialtool

How to improve damping in boring bars?

- Reducing critical damping constant improves vibrational damping of tool
- Damping ratio :

$$\varepsilon = \frac{c}{2\sqrt{mk}} \quad \text{---- 4}$$

c ← Damping constant

$2\sqrt{mk}$ ← Critical damping constant

- Replacing with **low weight to high strength** ratio material i.e. Cellular solids
- Using **high energy absorbing** structure i.e. cellular
- Using tuned mass dampers in tool.

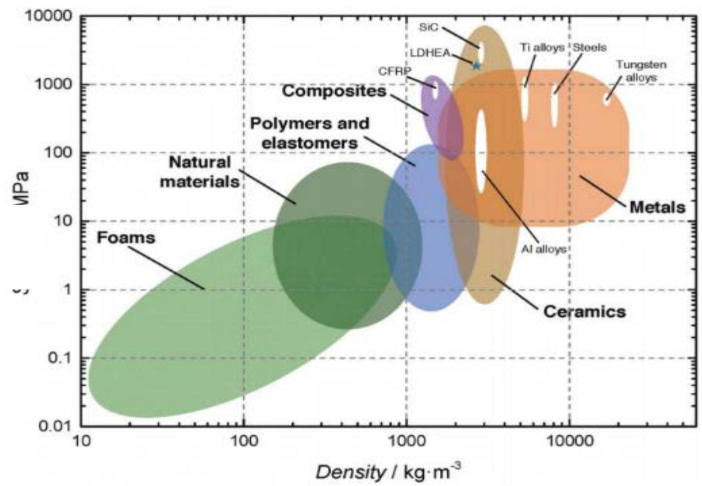


Fig. 23 Strength to weight ratio of engineering materials

Source : North Carolina State University, Materials research letters

Fig.24 Tuned mass dampers
Source : Sandvik coromant

Concluding remarks

- Damping plays a major role **improving surface quality** during boring
- **Overhang length** of tool can be increased in damped boring bar
- Replacing conventional solid tools with **low weight to high strength material** improves damping
- Damped boring bars **reduces operational cost**
- **Metal foams** has low weight to strength ratio i.e. Cymat, Alulight, Alporas, ERG, Inco
- **Cellular structured** solids has high energy absorbing capacity

Boring tool selection

Overhang Lengths

Selection of overhang length for different boring tool materials.

Steel boring bars:	Up to 4 x D
Carbide boring bars:	Up to 6 x D
Steel damped boring bars short design:	Up to 7 x D
Carbide reinforced damped boring bars:	Up to 14 x D

Source: Sandvik Coromant Manual, How to reduce vibration in metal cutting

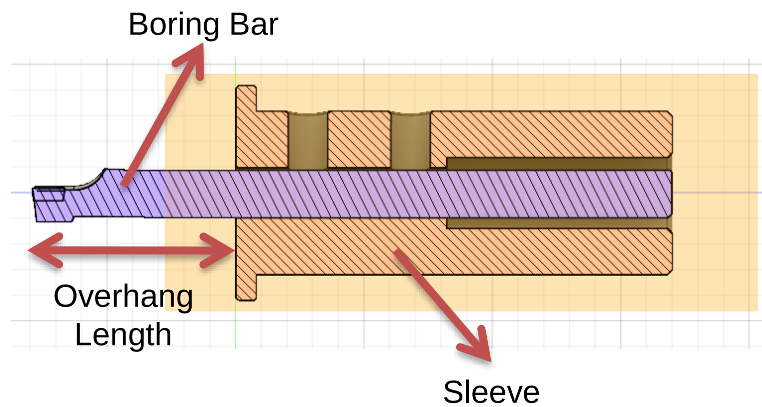


Fig.25 Overhang length

Fig.26 Boring bars – BB1 & BB2

Properties	BB1	BB2
Size – Dia/length (mm)	10/125	10/125
Material	Steel (with alloying elements)	Steel
Cross Section	Hollow	Solid
Cost (INR)	11,250	3,500

Table.1 Properties of tool

BB1 Specifications

1	2	3	4	5	6	7	8	9
A	10	K	S	C	L	C	R	06

A	Steel shank with coolant hole

10
10 mm

K
125 mm

S
Screw on

C
Rhombic 80°

L
95°

C
7° Positive

R
Right Hand

Inscribed circle of insert	6.35
Rhombic 80°	06

Benchmarking data

EXPERIMENTAL MODAL ANALYSIS – FREE FREE CONDITION

Parameter	BB1	BB2
Natural Frequency(Hz)	2908	2846

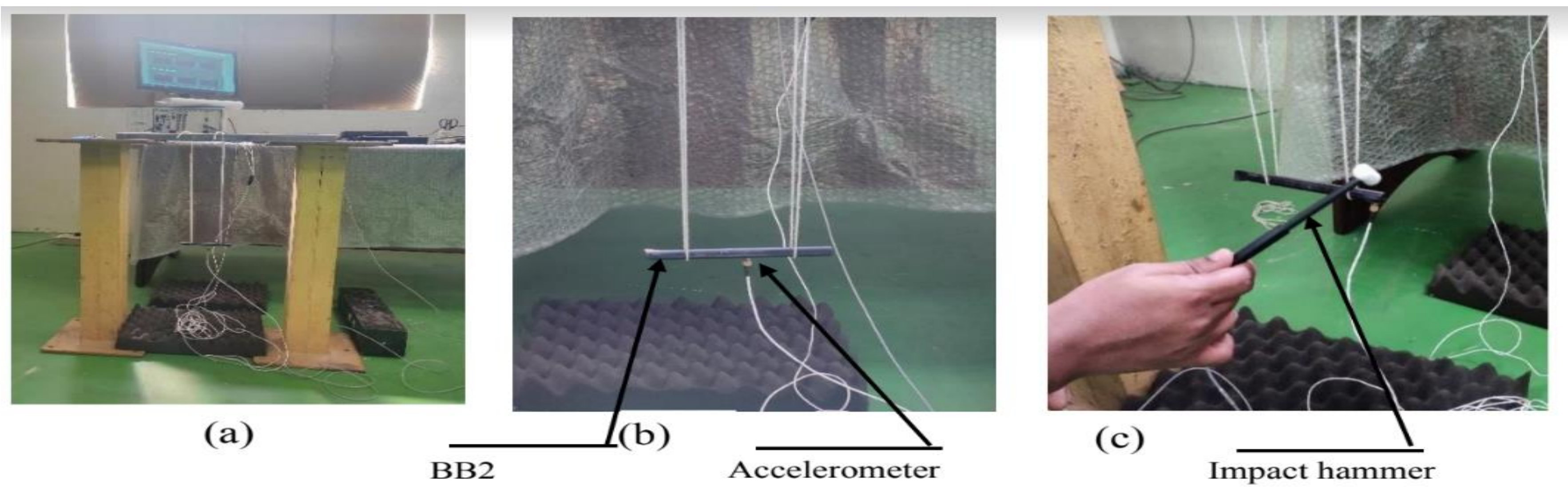
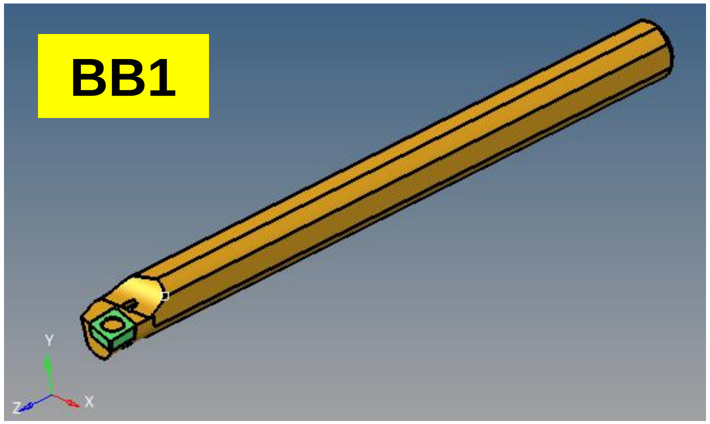
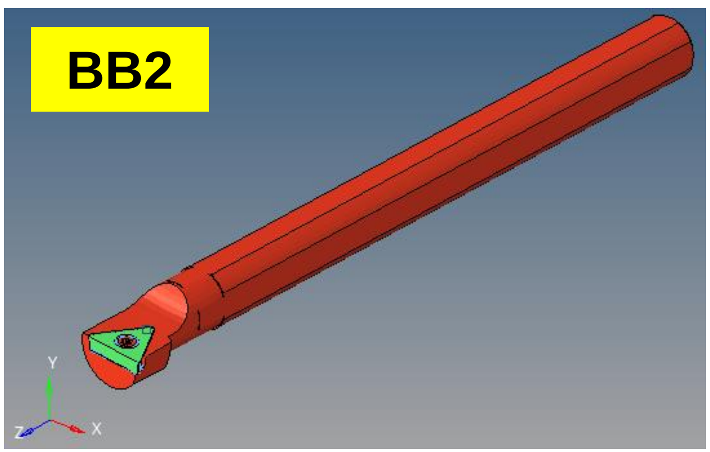


Fig. 27 (a-c) Experimental modal analysis setup and testing

BORING BAR FEA - MODAL ANALYSIS

GEOMETRY AND MATERIAL





TOOL :BB1

MANUFACTURER: SANDVIK COROMANT

MASS : 0.064 Kg

COOLANT DIA :3mm

TOOL :BB2

MANUFACTURE: WIDIA

MASS : 0.069 Kg

PART	MATERIAL	YOUNGS MODULUS	POISON RATIO	DENSITY
BORING BAR	STEEL	210GPa	0.3	7890 Kg/m3
INSERT	CARBIDE	600GPa	0.2	14800 Kg/m3
SLEEVE	STEEL	210GPa	0.3	7890 Kg/m3

Table.2 Mechanical properties of boring tool

Preprocessor : Hyper mesh

Solver : OptiStruct

Postprocessor : Hyper view

MESH CRITERIA

Element size : 1 mm

Element type : 3D tetrahedral second order

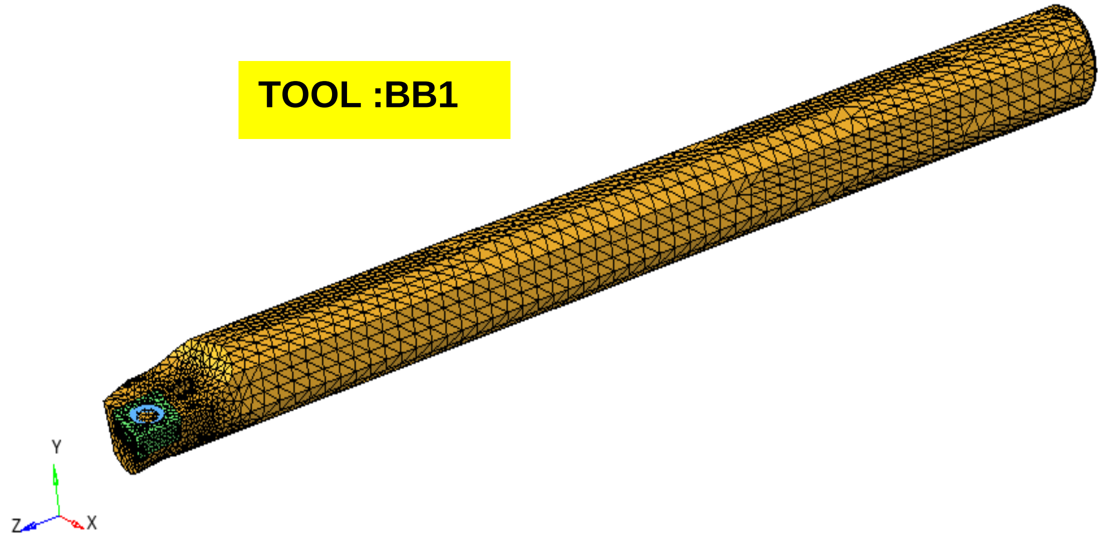
Tet collapse : 0.2

Number of elements

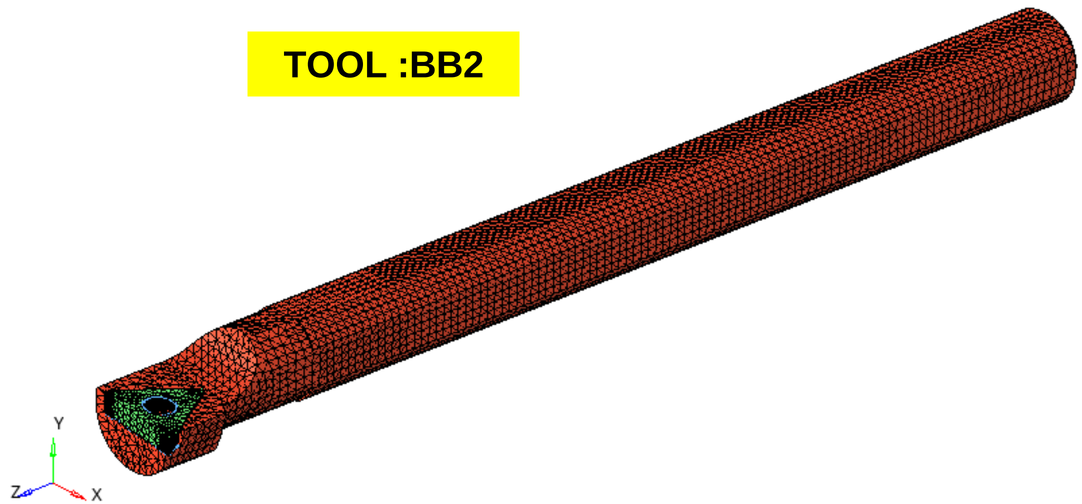
BB1 = 57071

BB2 = 60915

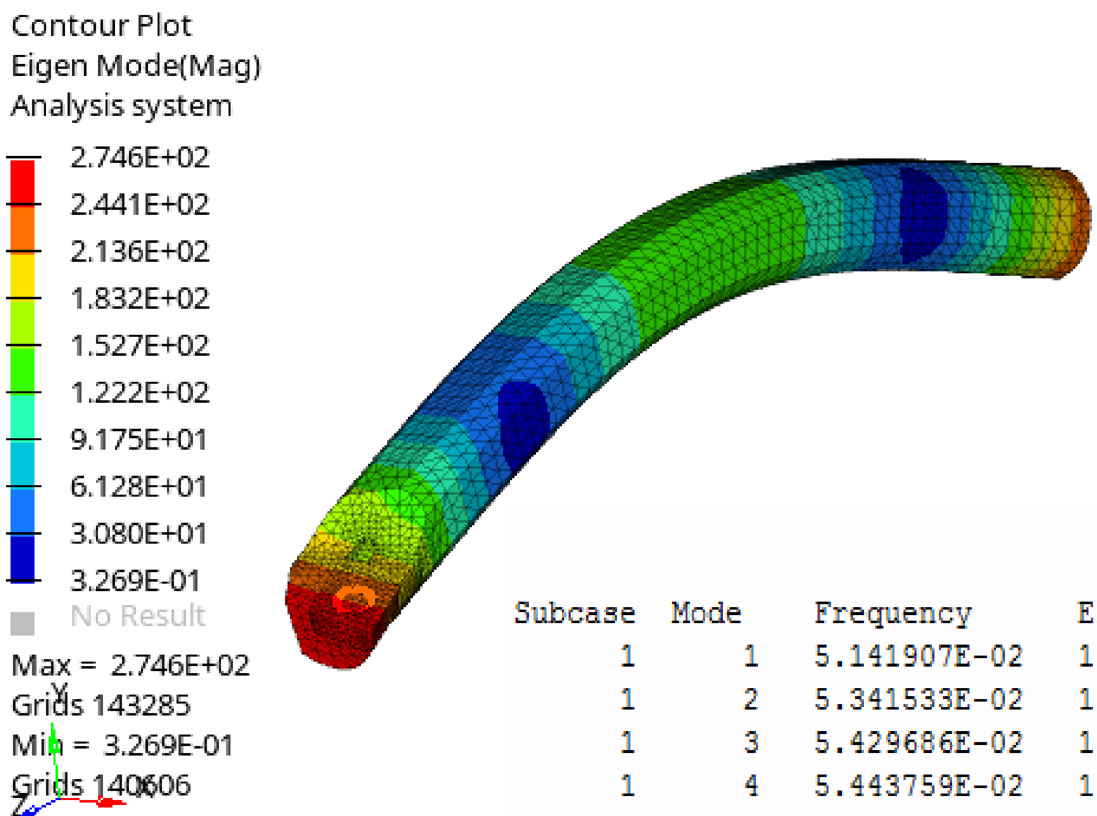
TOOL :BB1



TOOL :BB2



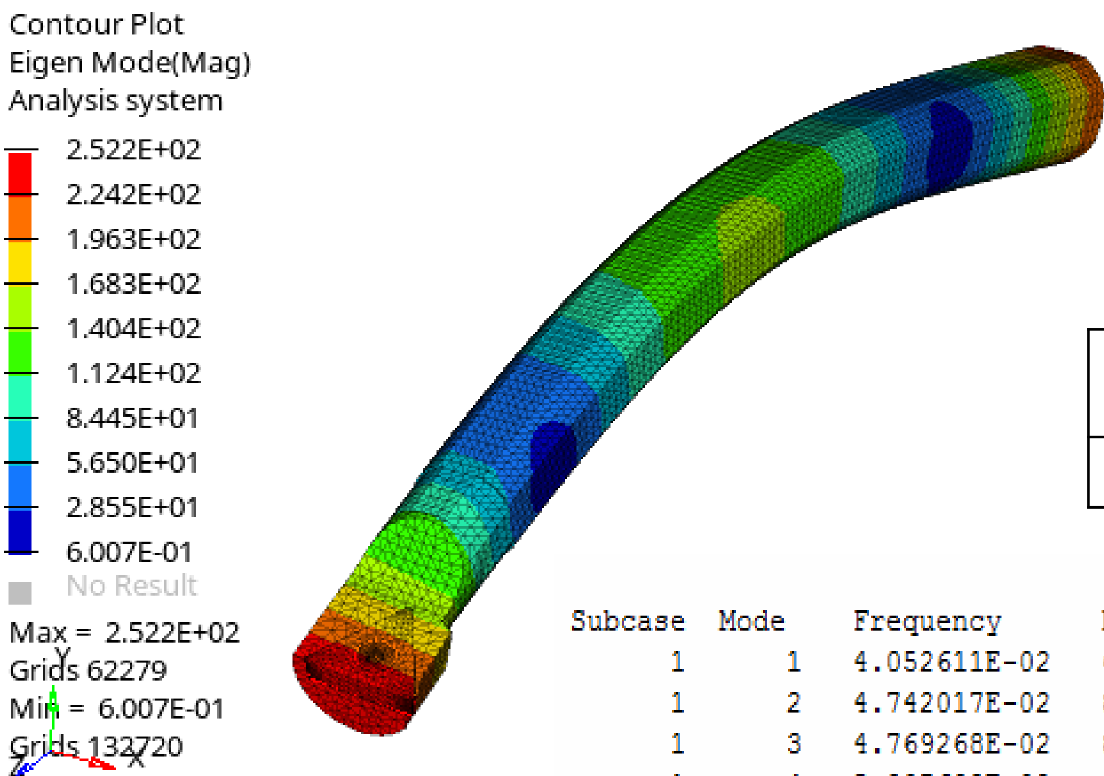
MODAL ANALYSIS - FREE FREE CONDITION



TOOL :BB1

1ST MODAL FREQUENCY	EXPERIMENTAL RESULT
2964 Hz	2908Hz

Subcase	Mode	Frequency	Eigenvalue	Generalized Stiffness	Generalized Mass
1	1	5.141907E-02	1.043778E-01	1.043778E-01	1.000000E+00
1	2	5.341533E-02	1.126397E-01	1.126397E-01	1.000000E+00
1	3	5.429686E-02	1.163883E-01	1.163883E-01	1.000000E+00
1	4	5.443759E-02	1.169924E-01	1.169924E-01	1.000000E+00
1	5	5.865880E-02	1.358395E-01	1.358395E-01	1.000000E+00
1	6	6.449059E-02	1.641922E-01	1.641922E-01	1.000000E+00
1	7	2.964649E+03	3.469816E+08	3.469816E+08	1.000000E+00
1	8	3.068312E+03	3.716712E+08	3.716712E+08	1.000000E+00
1	9	7.812315E+03	2.409457E+09	2.409457E+09	1.000000E+00
1	10	8.063843E+03	2.567106E+09	2.567106E+09	1.000000E+00



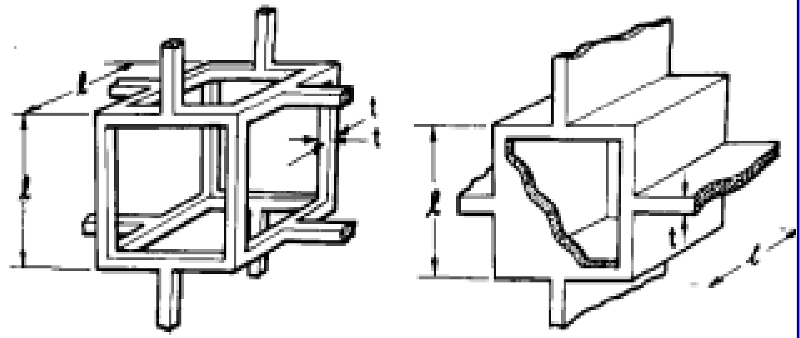
TOOL :BB2

1ST MODAL FREQUENCY	EXPERIMENTAL RESULT
2718 Hz	2846 Hz

Subcase	Mode	Frequency	Eigenvalue	Generalized Stiffness	Generalized Mass
1	1	4.052611E-02	6.483800E-02	6.483800E-02	1.000000E+00
1	2	4.742017E-02	8.877403E-02	8.877403E-02	1.000000E+00
1	3	4.769268E-02	8.979726E-02	8.979726E-02	1.000000E+00
1	4	5.307609E-02	1.112135E-01	1.112135E-01	1.000000E+00
1	5	5.415954E-02	1.158003E-01	1.158003E-01	1.000000E+00
1	6	5.562908E-02	1.221697E-01	1.221697E-01	1.000000E+00
1	7	2.718155E+03	2.916810E+08	2.916810E+08	1.000000E+00
1	8	2.822189E+03	3.144357E+08	3.144357E+08	1.000000E+00
1	9	7.139099E+03	2.012086E+09	2.012086E+09	1.000000E+00
1	10	7.426188E+03	2.177166E+09	2.177166E+09	1.000000E+00

Properties of Cellular solids

- The mechanical behaviour of cellular materials can be described by analysing the mechanisms by which the cells deform
- At **low relative densities**, it is made up of a network of rod like elements which form **open cells**. At **higher relative** densities (greater than 0.2) it is made up of a network of plate-like elements forming **closed Cells**
- **The results of the analysis depend on three parameters**:
  - The type of structure the cells form (for example, open or closed cells)
  - The volume fraction of solids, or relative density
  - Properties of the cell wall material



a) b)

Fig. 28 a) Open cell structure b) closed cell structure

Source : Gibson et al., 1981

Properties of cellular solids

Density Young's modulus Yield Strength Conductivity

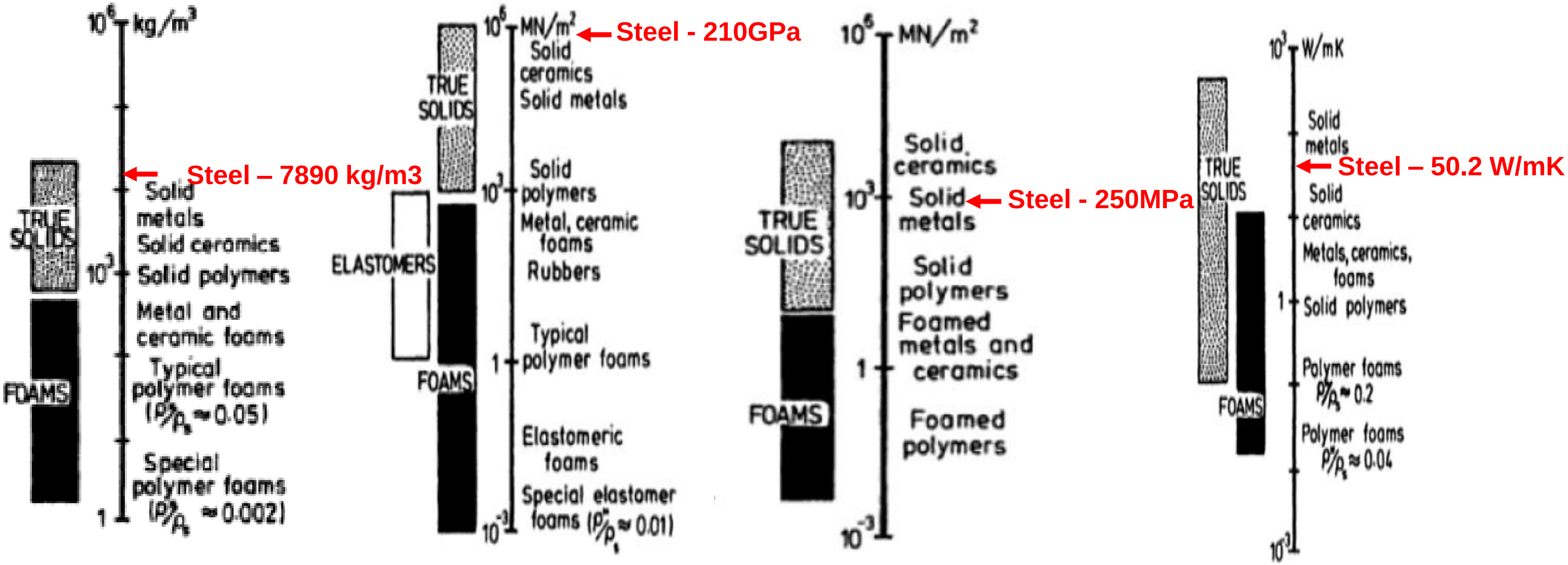


Fig. 29 Properties of cellular solids (a) Density (b) Young's modulus (c) Yield Strength (d) Conductivity

Source : Classification and selection of cellular materials in mechanical design,2019

Study on Cellular solids cell shape , size and topology

Cellular solids in nature

	Mechanical properties	Structure
Honeybee nest (Periodic)	High flexural , compressive strength	 (a)
Trabecular bone (stochastic)	Toughness under compressive and impact loading	 (b)
Dragonfly wing (Hierarchical)	Flexural rigidity , flexural stiffness	 (c)

Table.3 Cellular solids in nature

Fig. 30 Cellular solids in nature
(a) Honeybee nest **(b)** Trabecular bone
(c) Dragonfly wing.

Structure of cellular solids in nature

- Natural cellular solids are anisotropic, they have directional property
- Natural cellular solids have pore size of minimum 10 microns

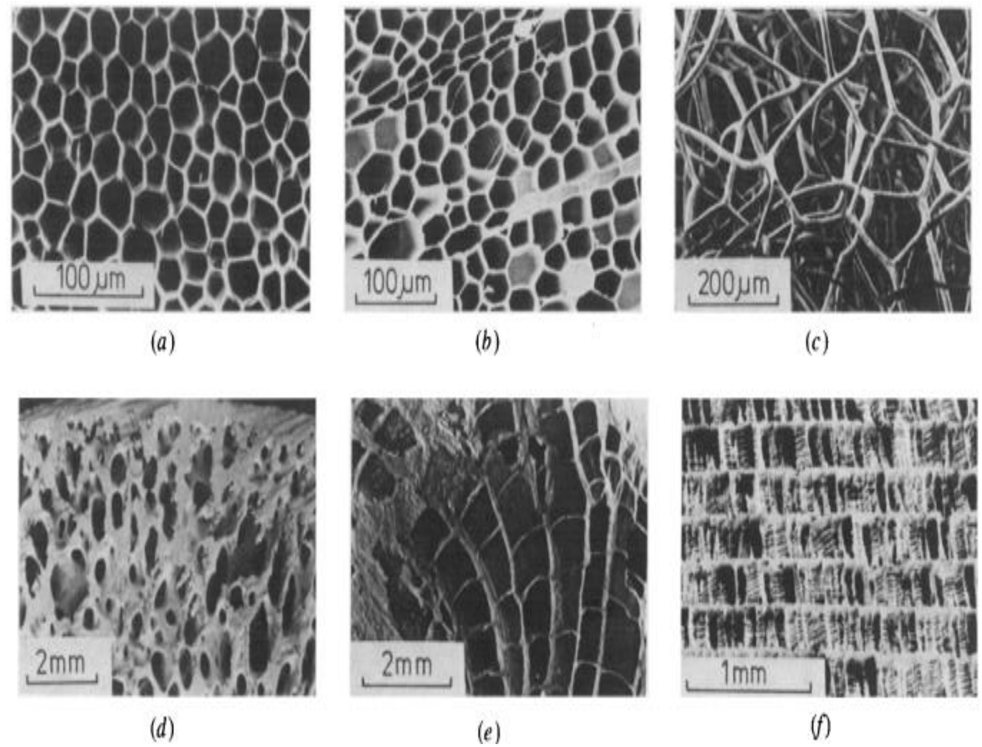


Fig. 31 Natural cellular materials: **(a)** cork, **(b)** wood, **(c)** sponge, **(d)** coral, **(e)** bone **(f)** cuttle bone.

Source : Gibson et al., 1981

Manufactured cellular solids

- Man made cellular solids are almost isotropic, meaning that their structure and their properties have no directionality
- Pore size of minimum 100 microns can be manufactured

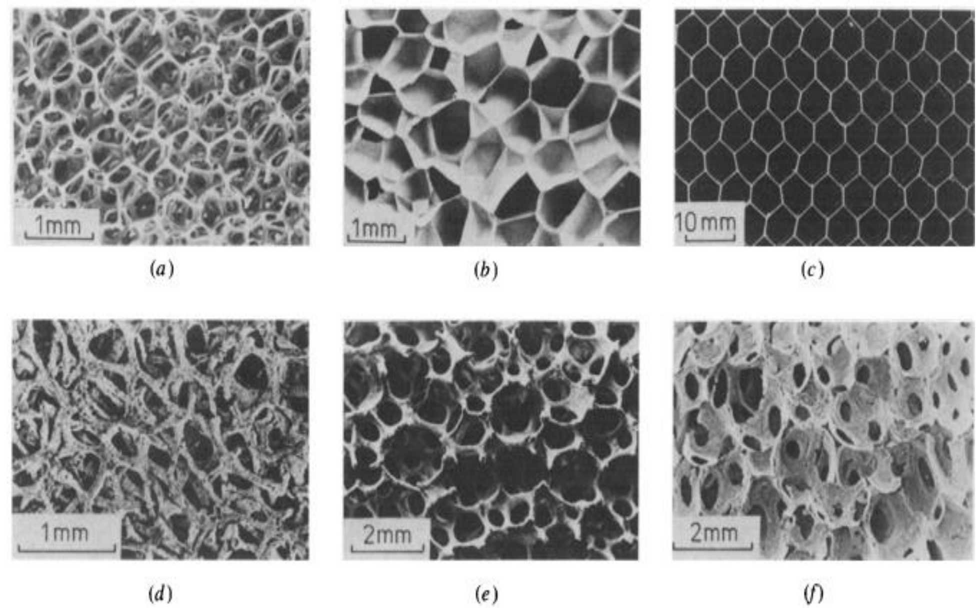


Fig. 32 Man-made cellular solids: (a) open cell polyurethane (b) closed cell polyurethane (c) aluminium honeycomb (d) copper (e) mullite (f) zirconia

Source : Gibson et al., 1981

Cell shape

- ➢ Periodic structure – Honeycomb has high flexural and compressive strength
- ➢ Selection of cell shape by Euler's law

F – E +V = 1 (Two dimension)

- C + F- E +V = 1 (Three dimension)

- ➢ Using **hexagonal prism** structure has **uniform infill** throughout
- ➢ 4 and 5 sided cells can be also implemented in hexagonal prism infill
- ➢ Implementation of hexagonal prism(polyhedral)infill isotropic property can be achieved

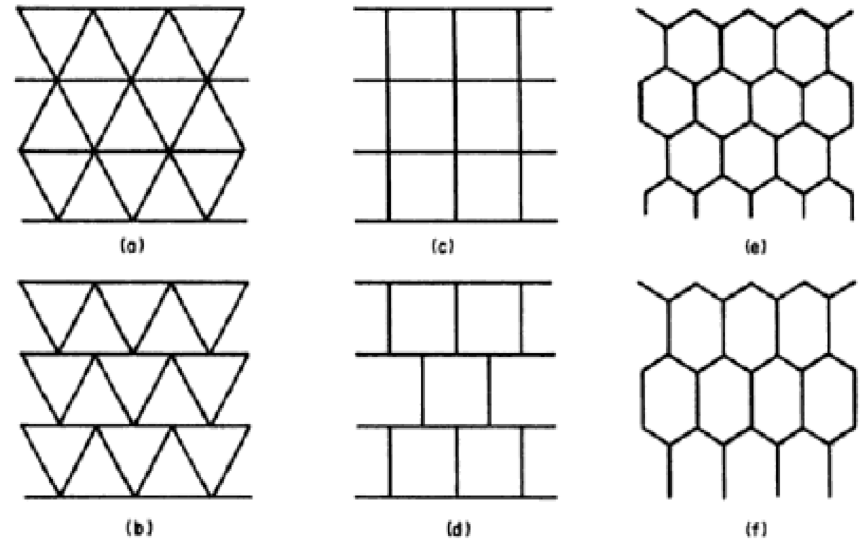


Fig. 33 Packing of two dimensional cell to fill space

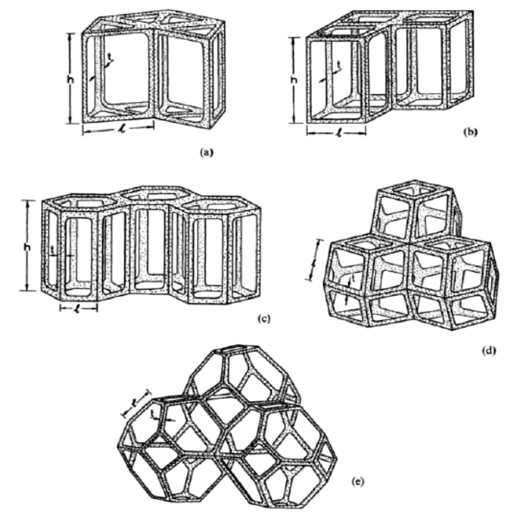


Fig. 34 Packing of polyhedral to fill space

Source : Gibson et.al , Cellular solids 1997

Cell size

- Parameters for selection of cell size
  - Vertical length of cell wall (h-height of cell wall)
  - Inclined length of cell wall (length of cell wall)
  - Thickness of the cell wall (t)
  - Angle between the vertical and inclined cell wall known as cell angle (θ)
  - Depth of the cell wall (d)
- Manufacturing by 3D printing limits the minimum size cell
- Minimum wall thickness manufactured by **3D printing** is **400 microns**

Source : *msesuppliers***,** www.3ders.org

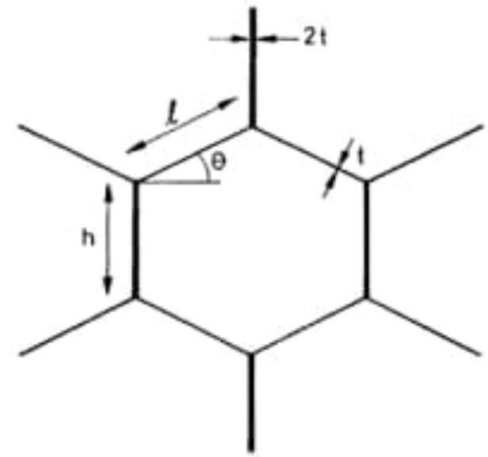


Fig.35 Honeycomb cell parameters

Source : Gibson et.al , Cellular solids 1997

Young's modulus $E_1^* = E_s \dfrac{\beta^3 \cos\theta}{(\alpha + \sin\theta)\sin^2\theta}$

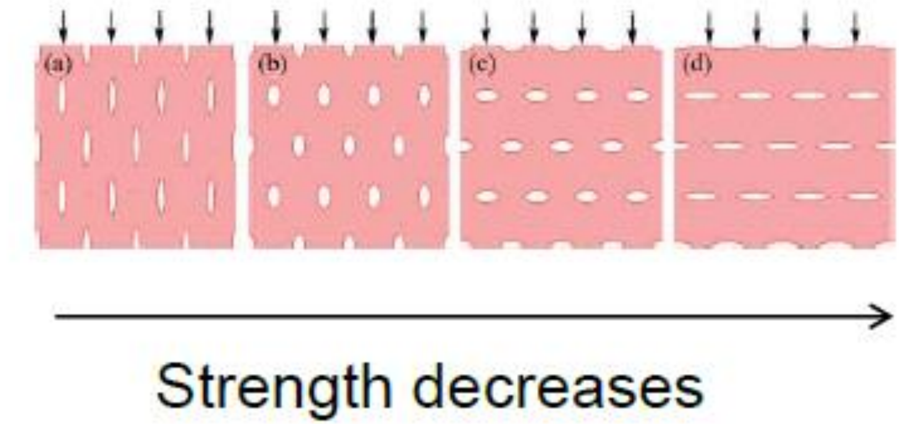
Shear modulus $G_{12}^* = E_s \beta^3 \dfrac{(\alpha + \sin\theta)}{\alpha^2(1+2\alpha)\cos\theta}$

Poison ratio $v_{12}^* = \dfrac{\cos^2\theta}{(\alpha + \sin\theta)\sin\theta}$

$\beta = t/l \quad \alpha = h/l$

Cell topology

- Pores having major axis parallel to the loading direction has better strength characteristics
- Large and low aspect ratio pores enhance flexural and compressive strength at the same relative density



Source: Tuncer, N., et al. *Materials Science and Engineering* A 528 (2011):

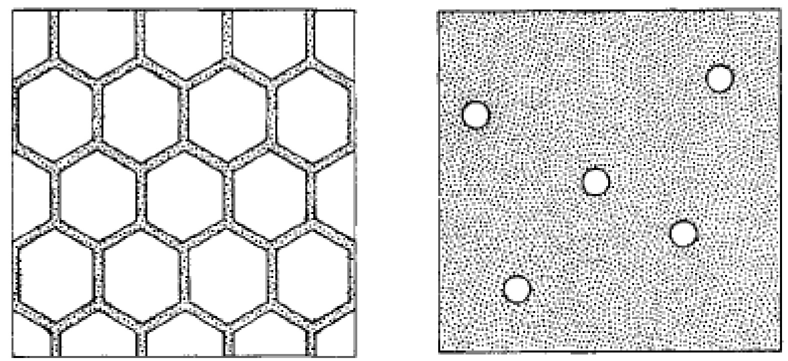


Fig.36 Comparison between a cellular solid and a solid with isolated pores

Source : Gibson et.al , Cellular solids 1997

Deformation mechanism of Honeycombs

Cell wall bending

- Layer-wise collapse perpendicular to loading direction
  - Oscillation in stress strain curve

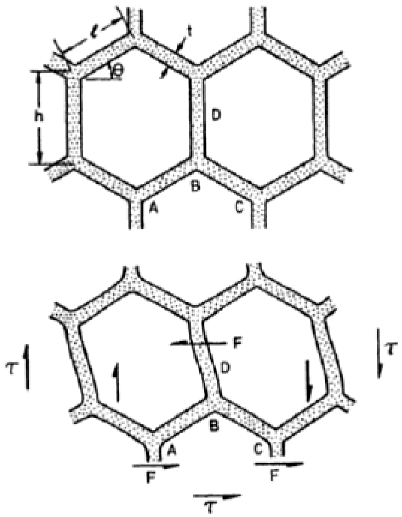


Fig.37 Cell wall bending

Cell wall buckling

- Shear localization occurs . Deformation at nearly constant applied stress by shear bands
  - Smooth stress strain diagram

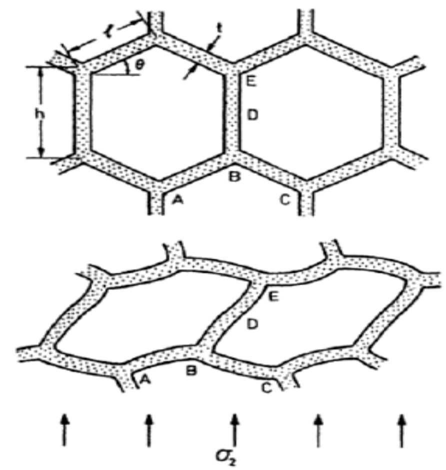


Fig.38 Cell wall buckling

Source : Gibson et.al , Cellular solids 1997

In-plane deformation

- In-plane occurs in x_1 and x_2 direction of the honeycombs
- **The resistance to the cell wall bending** and cell collapse goes up, giving a higher modulus and plateau stress and cell walls touch sooner, reducing the strain at which densification begins
- To calculate deformation
  - **Isotropic** - two independent elastic moduli (young's modulus E and shear modulus G) and size value of plateau stress (σ)
  - **Anisotropic** - (E_1 *, E_2 *, G_{12} *, λ_{12} *) two plateau stress (σ_1 *, σ_2 *)

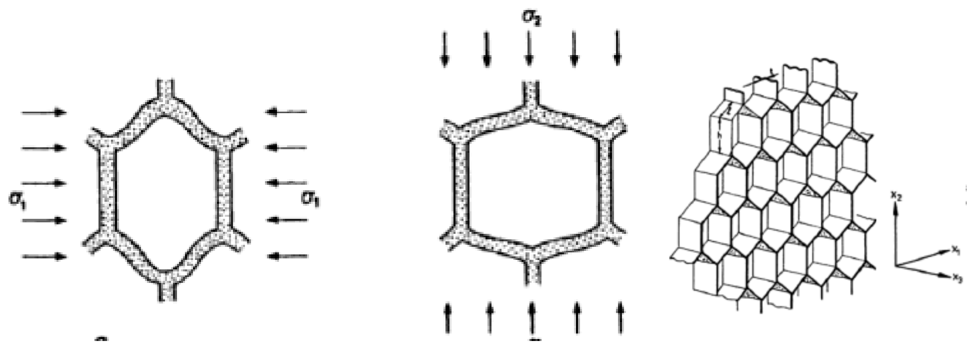


Fig.39 In-plane deformation of honeycombs by cell wall bending **(a)** In X_1 direction **(b)** X_2 direction

Source : Gibson et.al , Cellular solids 1997

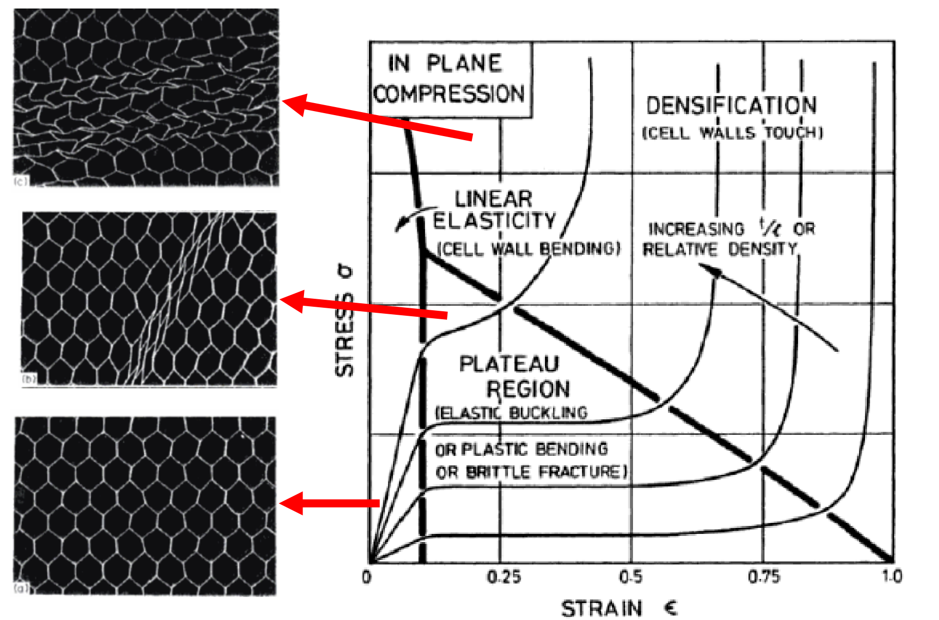


Fig.40 In-plane mechanism of aluminium in compression X_1 , X_2 direction

Out of plane deformation

- Out of plane deformation occurs in x_3 direction of the honeycombs.
- Cell wall thickness determines the stiffness and strength when it is loaded along the axis in the x_3 direction

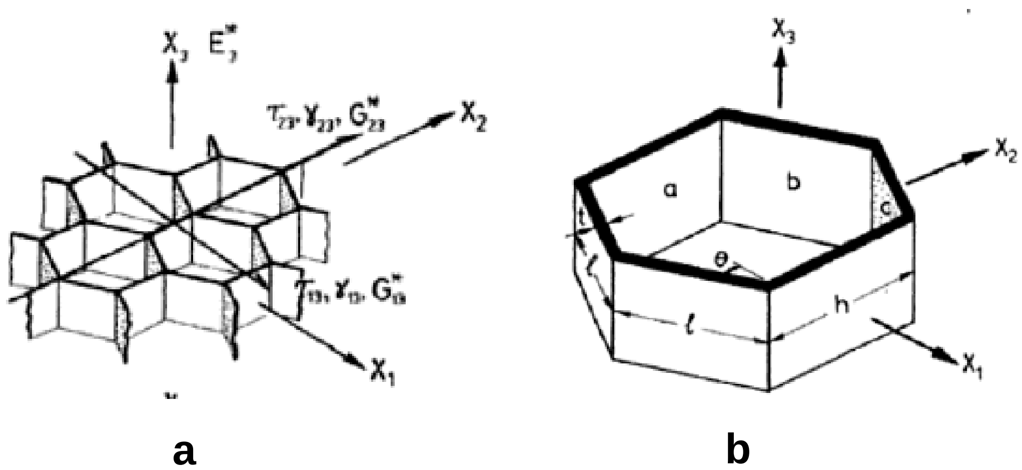


Fig.41 Out-plane deformation of honeycombs in X_3 direction

(a) In honeycombs **(b)** In unit cell

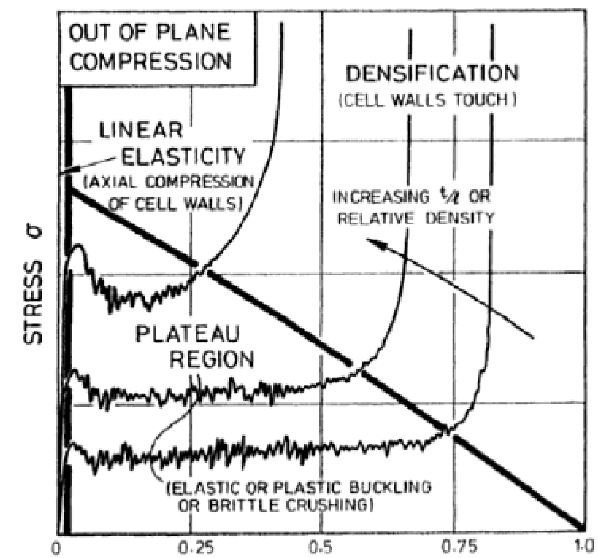
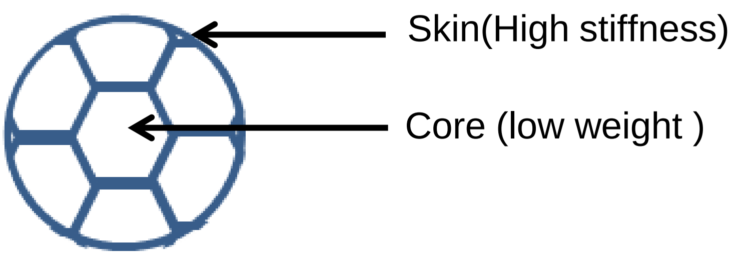


Fig.42 Out-plane mechanism of aluminium in compression in X_3 direction

Source : Gibson et.al , Cellular solids 1997

Why sandwich structure?

- Two solid surfaces(skins) separated by a lightweight core
- Separation of skins by core increases moment of inertia, with little increase in weight
- Sandwich plate exhibits high bending stiffness (flexural rigidity) for lower mass and has a low shear modulus which makes them a better source of damping
- Mechanical behavior of sandwich panel depends on properties of core , face and on its geometry



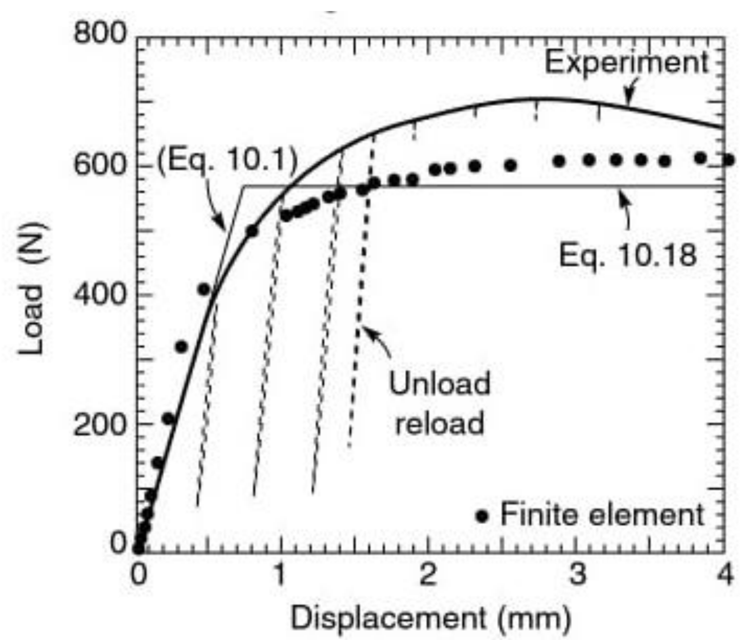


Fig. 43 Load vs displacement of sandwiched structure

Source *:* ASHBY R et al, Metal foams : A design guide M.F.., 2000

DESIGN OF HONEYCOMB STRUCTURE

Cellular solids relative density should be less than 0.3

RELATIVE DENSITY OF CELL AGGREGATE

$$\frac{\rho *}{\rho s} = \frac{2}{\sqrt{3}}\frac{t}{l}\left(1 - \frac{2}{\sqrt{3}}\frac{t}{l}\right) \text{ ---- Eq.26}$$

$$\frac{t}{l} = 0.365$$

$$\frac{\rho *}{\rho s} = \frac{t/l \ (h/L + l)}{(h/l + \sin\theta)\cos\theta} \text{ ---- Eq.27} \quad \theta = 30^{\circ}$$

Substituting t/l in Eq.2

$$\frac{h}{L} = 0.566$$

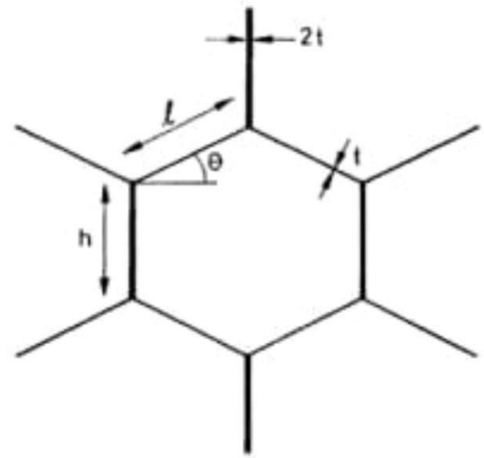


Fig.44 Honeycomb cell parameters

Source : Gibson et.al , Cellular solids 1997

Concluding remarks

- **Honeycomb structure** has high flexural strength and compressive strength
- Cell size of minimum 400 microns wall thickness can be only manufactured
- High flexural strength is resulted in topology having pore size major axis in loading direction

Selection of material

Properties	17-4 PH Stainless Steel	H13 Tool Steel	Inconel 625	Titanium (Ti6Al4V)
Density, ρ g/cm^3	7.75	7.80	8.44	4.83
Young's modulus, E –GPa	210	250	200	113
Ultimate tensile strength MPa	1050-1250	1420-1500	558-765	900-950
Poisson's ratio, ν	0.27-0.30	0.27-0.30	0.26-0.28	0.31-0.37
Cost (RS)(approx.)	12,000/Kg	17,000/Kg	12,000/Kg	20,000/Kg

Table.4 Materials for manufacturing cellular solids

Source : *Msesuppliers*, www.3ders.org

- Material is finalized based on availability of manufacturing resources

Why additive manufacturing for cellular materials ?

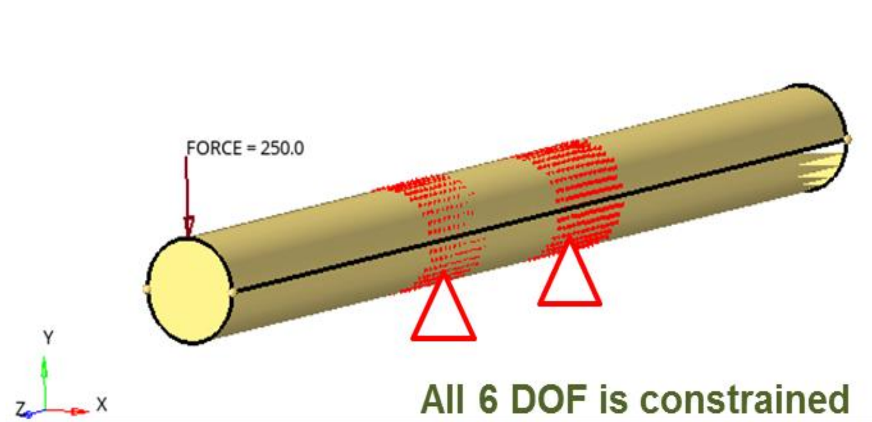
- **Additive manufacturing offers advantages**
  - Local tunability
  - Complex, Non-stochastic shapes
  - Low cost penalty for complexity
  - Multi-material

- **Additive manufacturing considerations**
  - Dimensional accuracy
  - Feature resolution
  - Defects
  - Cleaning
  - Inspection

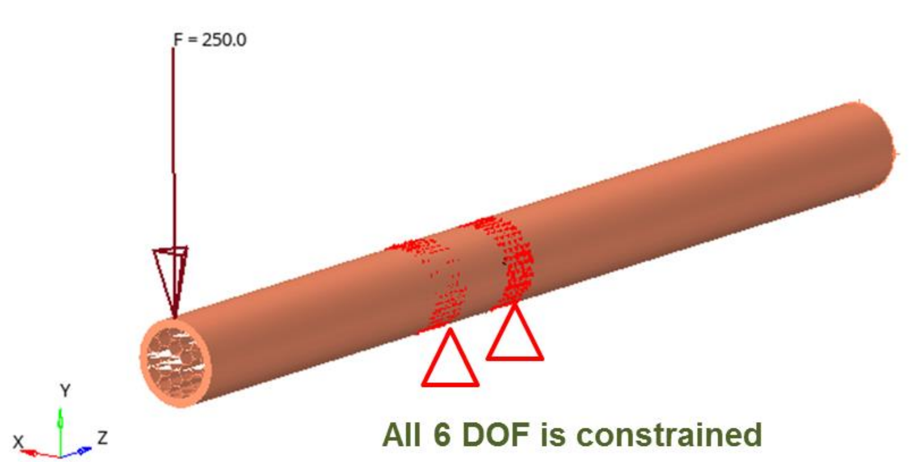
Linear static analysis

Loads and boundary condition

Solid structured bar

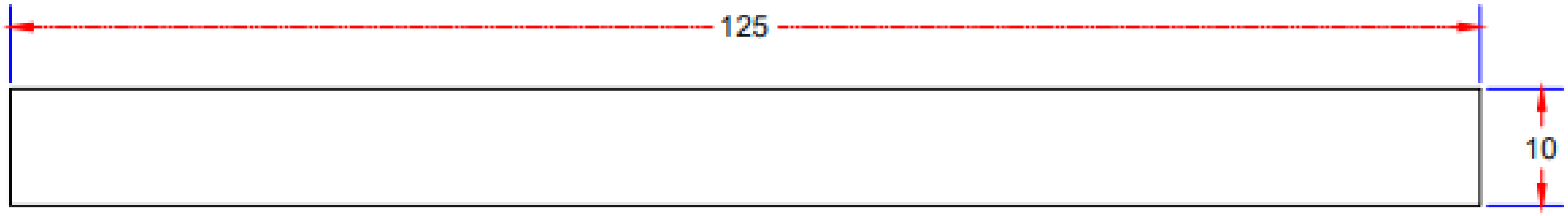


Honeycomb structured bar

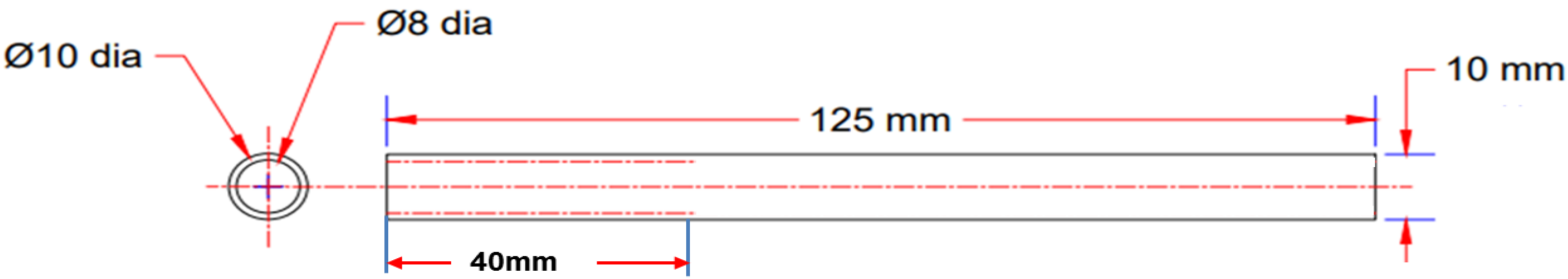


Specimen design

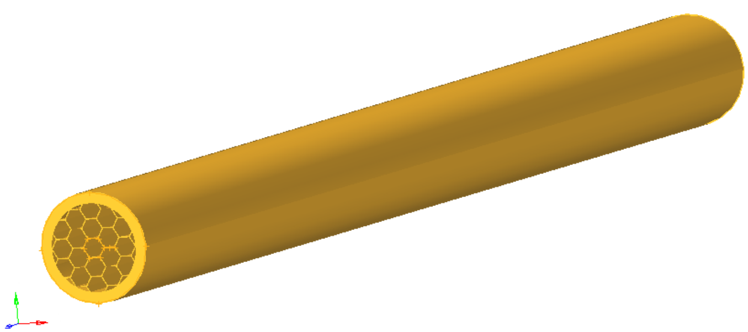
SOLID BAR

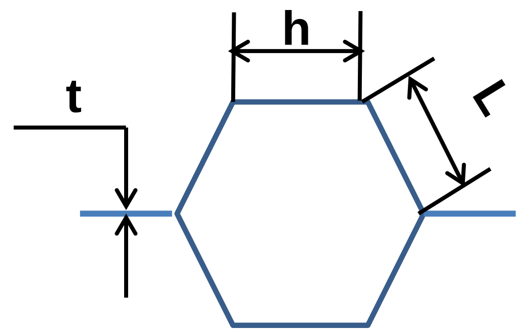


HOLLOW BAR



HOLLOW BAR FILLED WITH CELLULAR STRUCTURE





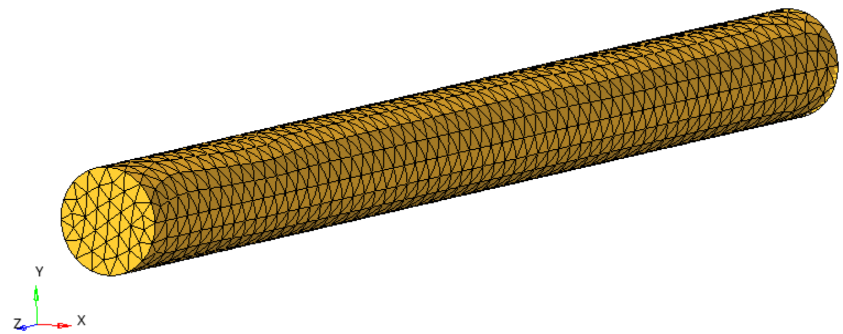
Finite element model

Preprocessor : Hyper mesh

Solver : OptiStruct

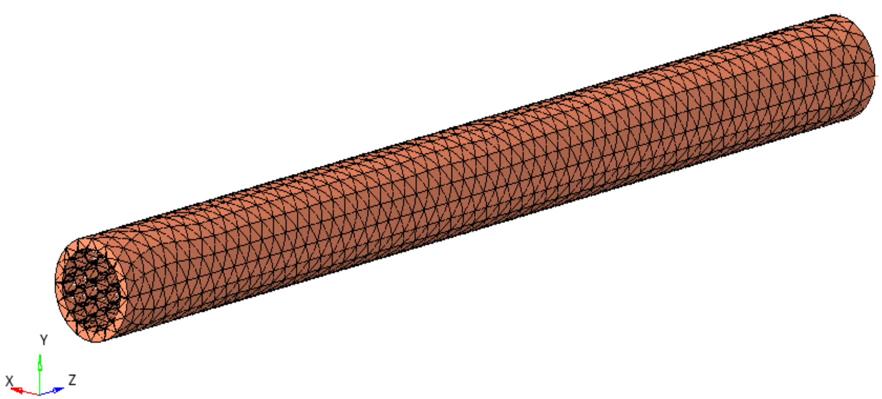
Postprocessor : Hyper view

Solid structured bar

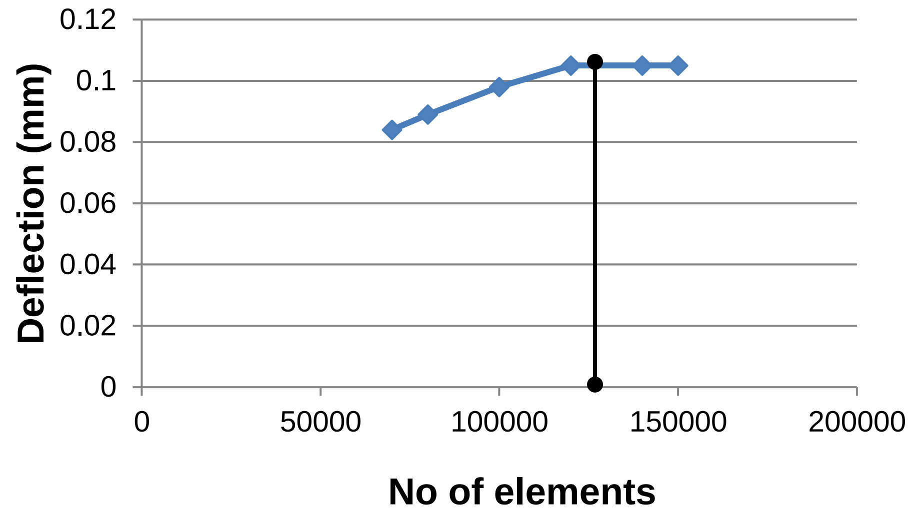


MATERIAL	YOUNGS MODULUS E	POISON RATIO ν	DENSITY ρ
STEEL	210GPa	0.3	7890 Kg/m3

Honeycomb structured bar



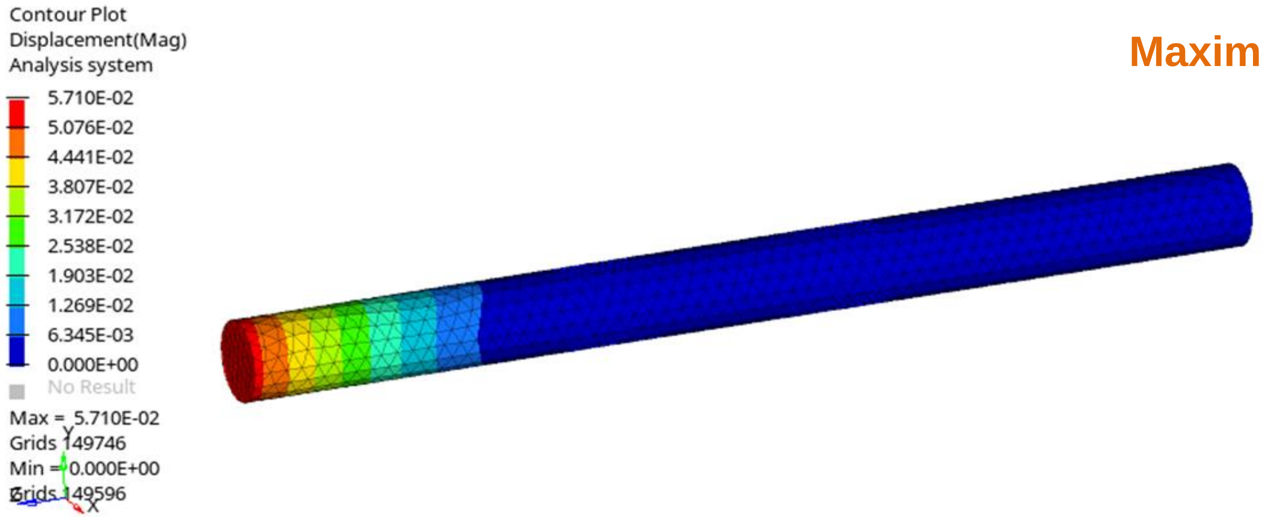
Mesh convergence study



Number of elements = 121649

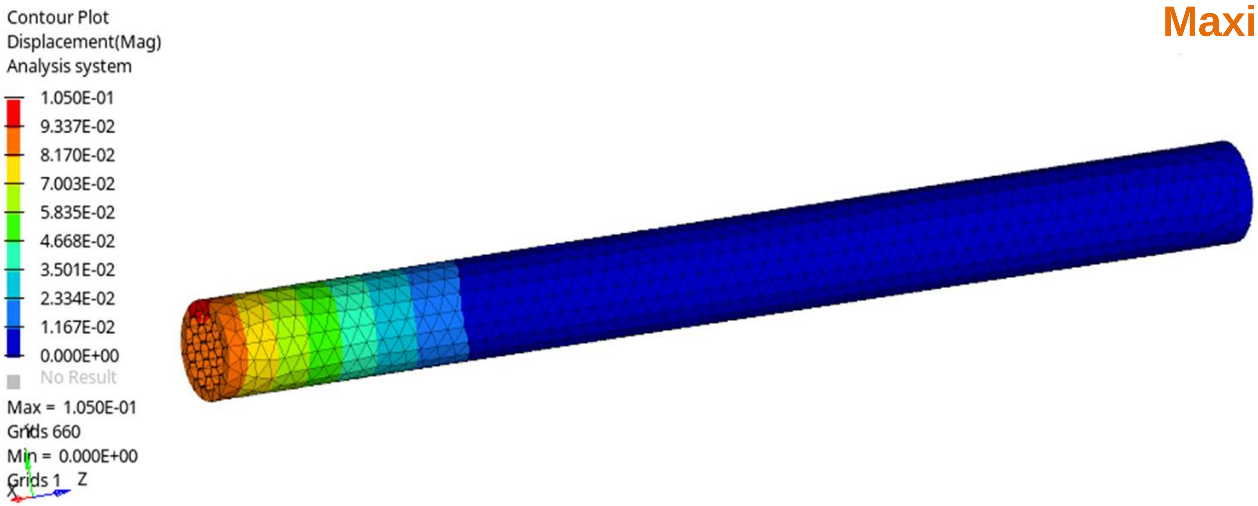
Displacement plot - Solid bar

Maximum displacement = 0.0571 mm



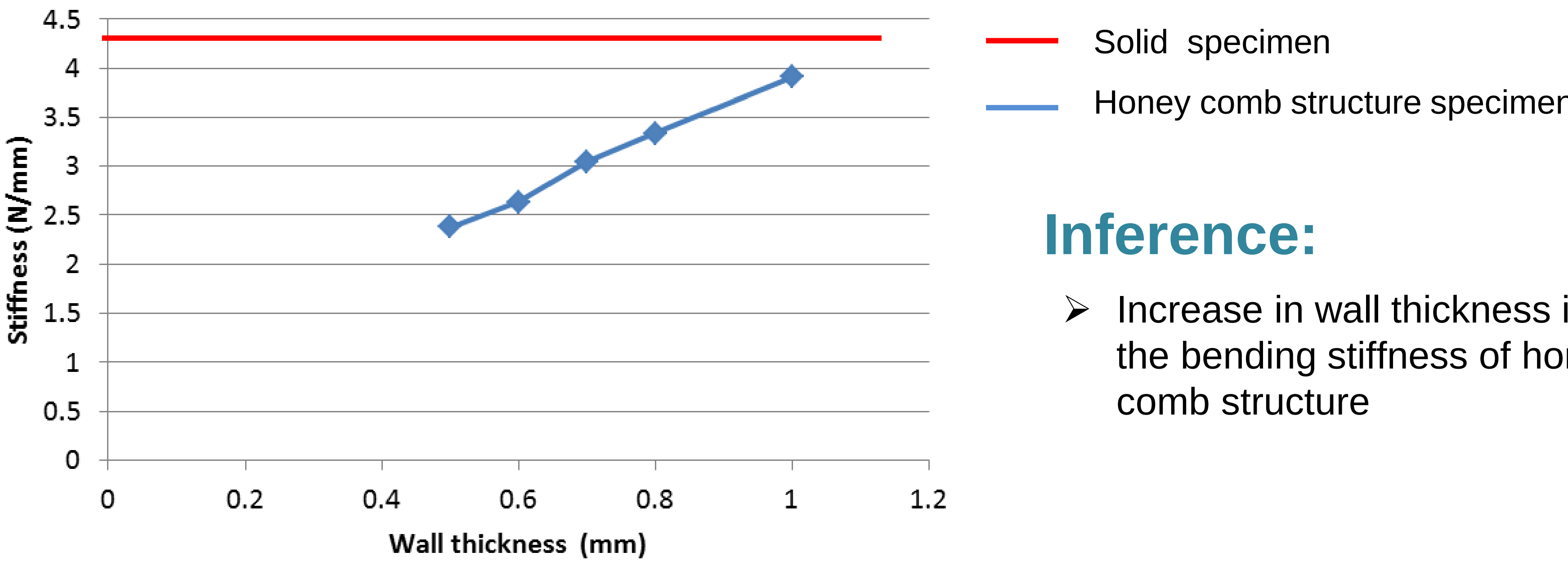
Honeycomb structure bar

Maximum displacement = 0.105 mm



Thickness (t) (mm)	Height (h) (mm)	Length (l) (mm)	Displacement (mm)	Stiffness (kN/mm)	Mass (kg)
0.5	0.70	1.38	0.105	2.380	0.034
0.6	0.85	1.67	0.095	2.631	0.039
0.7	0.98	1.94	0.082	3.048	0.041
0.8	1.12	2.22	0.075	3.333	0.046
1	1.40	2.77	0.064	3.906	0.053
Solid bar			0.0571	4.378	0.077

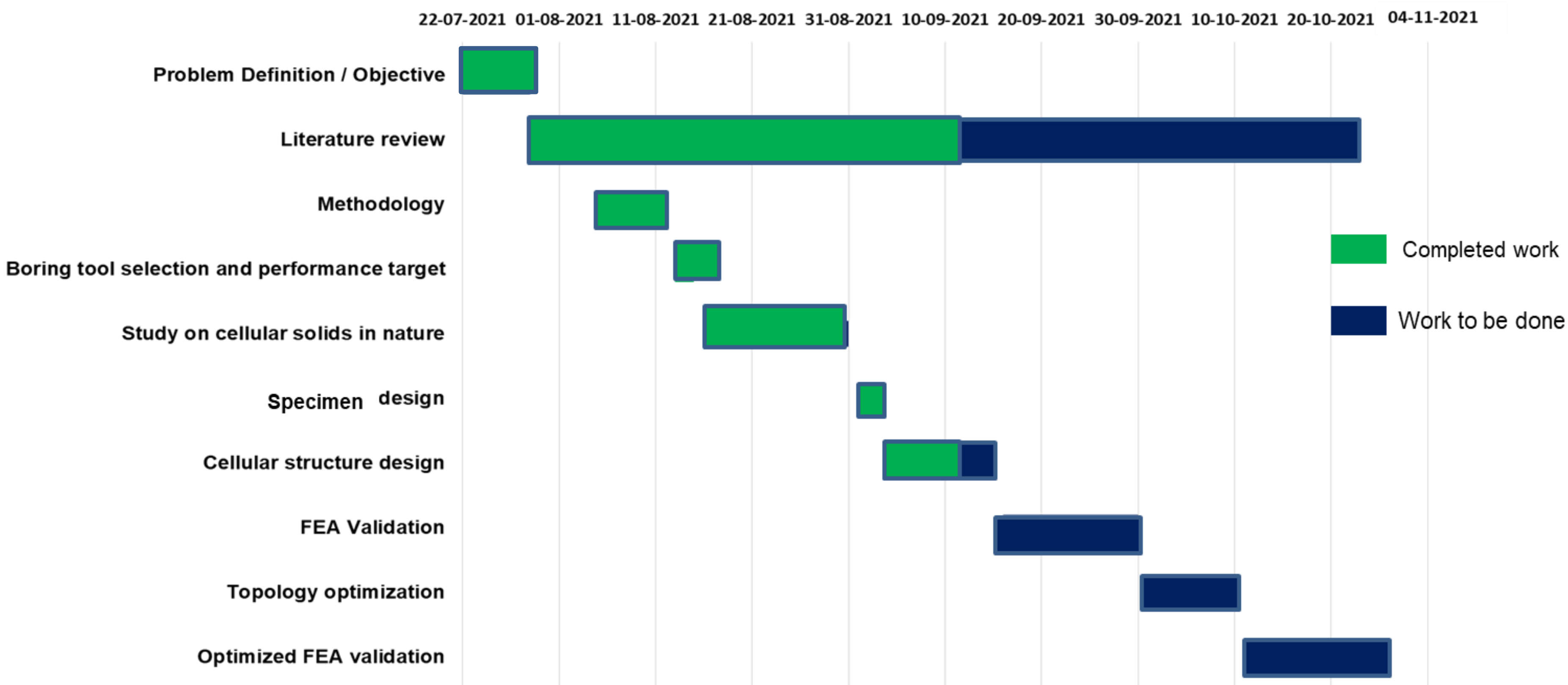
Table.5 FEA results of honeycomb structure bar



Inference:

- Increase in wall thickness improves the bending stiffness of honey comb structure

Gantt chart



TASK	Problem Definition / Objective	Literature review	Methodology	Boring tool selection and performance target	Study on cellular solids in nature	Specimen design	Cellular structure design	FEA Validation	Topology optimization	Optimized FEA validation
START DATE	22-07-2021	29-07-2021	05-08-2021	13-08-2021	16-08-2021	01-09-2021	04-09-2021	16-09-2021	01-10-2021	11-10-2021
DAYS TO COMPLETE	7	84	7	2	15	2	11	14	9	10

Thank you