

# STUDY OF CELLULAR STRUCTURES: ANALYSIS OF ELASTIC DEFORMATION OF ALUMINIUM HONEYCOMBS

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**ABSTRACT** - Cellular solids are an assembly of a number of cells forming solid edges or faces and occupying space. Honeycombs are a two-dimensional array of such cells, forming polygons for faces. It exists in nature as wood, coral etc. They are also manufactured and used widely as polymeric foams. A background study of honeycomb history has been conducted from Gibson and Ashby's model, which describes a relationship between the Young's Modulus of a regular hexagonal honeycomb cell and that of the material from which the honeycomb cell has been made, to Balawi and Abot's model of commercial honeycombs with double cell wall thickness. This work investigates the in-plane elastic properties of regular aluminium honeycomb cells of  $t/l$  ratios 0.3 and 0.005 using ANSYS Mechanical. Software implications have been used to carry out comparisons between the trends of elastic deformation, normal vs shear stress and maximum principal stress vs maximum principal elastic strain of honeycomb cells as a whole and of the outer slant edge of the cell. In-plane elastic properties of commercial honeycomb cell of  $t/l$  ratio 0.005 have, also, been compared with the regular honeycomb cell of the same ratio.

**Keywords:** Cellular Solids, Honeycombs, In-plane elastic properties, Commercial Honeycombs, Shear stress, Normal stress, Maximum Principal Stress, Maximum Principal Elastic Strain

## 1. INTRODUCTION

Cellular solids are an assembly of a number of cells forming solid edges or faces and occupying space. Honeycombs are a two-dimensional array of such cells, forming polygons for faces. The term 'honeycomb' represents all 2-D cellular solid forming polygons. Foams are a three-dimensional array of cells, which occupy space. The cells, here, form polyhedral solids, which are solids made up of plane surfaces. Foams are of two types, open celled foams and closed celled foams. If the cells of a solid are connected by open surfaces only, then it is called an open celled foam. On the other hand, if the cells of a solid are completely separated out from the neighbouring cells by solid faces, then it is called a closed celled foam.

The most important feature of a cellular solid is its relative density, that is, the ratio of the density of the cellular solid and that of the solid from which the cells are made. As this density ratio increases, the pore spaces shrink and the cell wall thickens. Above a relative density of about 0.3, there is a transition from cellular solids to solid structure merely containing pores. Therefore, true cellular solids are considered to have a relative density of less than 0.3.

The objective of this research article is to develop ANSYS models of two aluminium honeycombs of  $t/l$  ratios 0.005 and 0.3 and analyse and compare their in-plane elastic properties, in terms of deformation, normal stress, shear stress, maximum principal stress and maximum principal elastic strain, under uniaxial compressive loading in the two in-plane directions, namely X and Y, and to study the elastic in-plane deformation of commercial honeycombs of  $t/l$  ratio 0.005 under uniaxial compressive loading. These ratios are taken so that the properties of true cellular solids can be compared with solid structures containing pores.

## 2. PROPERTIES

The physical, thermal and chemical properties of cellular solids can be measured in the same way as that of true solids. Foaming in various materials expands the scope of usage of that material. It creates an extension of properties, paving way for more advanced engineering applications, which otherwise would not have been possible without it. On the basis of the distribution of solid in cells and edges, the properties of cellular solids may vary. Hence, quantifying the structure, to understand the various properties of cellular solids has to be the initial step. Geometrical aspects of cell structure such as relative density and anisotropy and topological aspects of cell shape such as number of neighbouring contacts and edge and face connectivity are also pivotal to understanding the mechanical properties of cellular structures.

## 3. APPLICATIONS

Cellular solids are manufactured and used widely as polymeric foams, which are used in everything from crash

padding of an aeroplane to disposable cups. It is now easier to foam not only polymers, but also metals used for cushioning and insulation. The deHavilland Mosquito aircraft (a WWII bomber) is considered to be the first industrial scale application of honeycombs. Commercially available honeycombs usually have low relative density [1]. Polymeric and glass foams are used for thermal insulation of booster rockets for space shuttle, refrigerated trucks, railway cars and ships carrying liquid natural gas. They are also used in skis, racing yachts and portable buildings. The cuttlebone in cuttlefish is an example of an elaborate sandwich panel. The skull is made up of two layers of dense bones separated by a lightweight spongy core of cancellous bone. They are extensively used as flotation in boats and as supports for floating structures. Foams and honeycombs have special advantages as filters, carriers for inks and dyes, water-repellent membranes etc.

#### 4. BACKGROUND

As mentioned before, the deHavilland Mosquito aircraft (a WWII bomber) is considered to be the first industrial scale application of honeycombs (Tom, 1997<sup>[3]</sup>; Hoffman, 1958<sup>[4]</sup>). In the beginning, honeycombs were used as sandwich structures for high out-of-plane stiffness and as low-density impact energy absorption materials (Zhao and Grrard, 1998<sup>[5]</sup>; Vinson, 1999<sup>[6]</sup>; Khan, 2006<sup>[7]</sup>). Olympio and Gandhi in 2007<sup>[8]</sup>, Bubert et al. in 2008<sup>[9]</sup> and Jaehyung et al. in 2010<sup>[10]</sup> proposed high shear strength and strain honeycomb structures. Kwangwon Kim et al., in 2012<sup>[11]</sup> proposed FEA models of modified Auxetic honeycombs, honeycombs with negative Poisson's ratio, as high strain flexures. Yanping and Hong <sup>[12]</sup> in 2010 gave a detailed review of Auxetic cellular structures.

Garrard (1949) <sup>[13]</sup>, Charles and Ralph (1951) <sup>[14]</sup> and Horvay (1952) <sup>[15]</sup> studied the overall elastic properties of sandwich plates in the assembled situation. While Akasaka and Takagishi (1959) <sup>[16]</sup>, Hoffman (1958) and Kelsey et al. (1958) <sup>[17]</sup> studied the in-plane Poisson's ratio of hexagonal honeycomb cores and the effective transverse shear moduli. Habip (1964) <sup>[18]</sup>, Lui and Habip (1965) <sup>[19]</sup> worked towards attaining efficiency in numerical analysis. (Frostig, 1998) <sup>[20]</sup> showed that for this, by application of a composite or sandwich shell theory, a continuum model replaces the honeycomb core and analysed in terms of their effective properties.

Cell geometries were also proposed by many such as, Theocarlis et al. (1997) <sup>[21]</sup> (star-shaped microstructure), Grima et al. (2008b) <sup>[22]</sup> (Chiral honeycombs), Larsen et al. (1997) <sup>[23]</sup>, Smith et al. (2000) <sup>[24]</sup>, Gaspar et al. (2005),

Kwangwon Kim et al. (2012) <sup>[25]</sup> and Jaehyung et al. (2010) <sup>[26]</sup>, but were later proved to have no practical purposes.

Lorna Gibson and Michael Ashby (1988) <sup>[27]</sup> considered the honeycomb cell walls to be flexures that is fixed at one end and guided at the other end, using the Cellular Material Theory, which is a cell wall bending model. Later on, Masters and Evans (1996) <sup>[28]</sup> modified the model by introducing three mechanisms of flexing, hinging and stretching. Hohe and Becker (2002) <sup>[29]</sup> presented a thorough examination of the homogenization methods and material models. Balawi and Abot (2007b) <sup>[30]</sup> and Balawi and Abot (2008) <sup>[31]</sup> proposed a model for commercial honeycombs, which are honeycombs with double cell wall thickness in the vertical direction.

#### 5. MECHANICS OF HONEYCOMBS

When a honeycomb is compressed in-plane, the cells walls will first bend giving linear deformation. After the critical value of the strain is reached, the cells collapse by elastic buckling, plastic yielding, brittle fracture or creep, depending upon the nature of the cell wall material. Furthermore, as the collapse continues and the opposing cell walls begin to touch each other, and the collapse ends densifying the structure and increasing the stiffness rapidly. Elastomeric materials collapse by elastic buckling. This collapse is recoverable. In brittle materials, the collapse is by brittle fracture of cell wall. While in materials with plastic yield point, the deformation is by formation of plastic hinges at the section of maximum moment in the bent cell walls. The collapse is irrecoverable in both of these cases.



**Image 1:** The in-plane and out-of-plane directions of a honeycomb which are X and Y, and Z respectively.

The in-plane stresses and strengths are lower as compared to the out-of-plane stresses and strengths because loading in the former directions make the cell walls bend. Study of in-plane properties shows the mechanism by which cellular solids deform and fail, while the study of out-of-plane properties gives us the details of the additional stiffness, which is primary in understanding the behaviour of natural honeycomb-like materials, such as wood. A regular hexagonal honeycomb with uniform cell wall thickness is isotropic. Such a structure has two

independent elastic moduli, a Young’s modulus  $E^*$  and a shear modulus  $G^*$ , for instance, and a single value of plateau stress  $\sigma^*$ .

The three main assumptions which make the study of the in-plane properties of honeycombs easier, as described by the Gibson and Ashby’s model, are:

1. The cell walls are linearly elastic and isotropic.
2. The deformations are small and, hence, small changes in geometry can be neglected.
3. The  $t/l$  ratio or the relative density is small and therefore, shear and axial contributions to the deformation can be neglected.

Gibson and Ashby carried out the analysis for the in-plane properties of a hexagonal honeycomb assuming that the inclined walls of a unit cell will deflect as a beam resulting in a dependence on the cubic wall thickness to wall length ratio,  $(t/l)^3$ . Furthermore, the deflection from axial deformation of the vertical walls is much lower than the deflection due to bending of the inclined wall, so it can be neglected for lower values of  $t/l$ . Masters and Evans modified the models presented by Gibson and Ashby by introducing the hinging of the walls at the intersection points of the inclined and vertical cell walls, which resulted in the dependence on the  $t/l$  ratio, resulting in lower effects on the overall in-plane properties of the honeycomb.

Commercial honeycombs have double cell wall thickness in the vertical direction. This double wall occurs as a result of most common production methods such as expansion and sheet corrugation [37]. The analysis of the in-plane properties neglects the vertical wall deformation, therefore, both regular honeycombs with uniform thickness and double cell wall thickness in the vertical direction will have the same in-plane properties.

Although, a thorough examination of this assumption shows that this cannot be the case. Experimental results show that for honeycombs with higher relative density, there is a difference between the elastic moduli where  $E_2^{eff}$  is higher than that calculated for  $E_1^{eff}$  (Balawi and Abot, 2007), although this difference is not very significant in commercial honeycombs. This may be due to the difference in the hole shapes during machining, faulty manufacturing processes, and the stress relieving process experienced by the studied honeycomb.

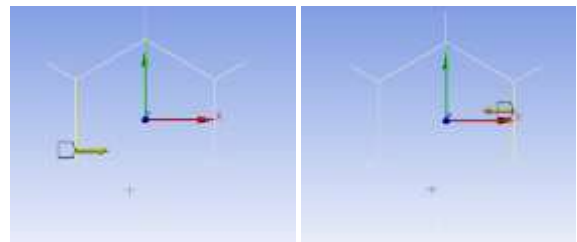
## 6. SPECIFICATIONS AND DESIGN

Two planar surfaces of aluminium hexagonal unit cells with  $t/l$  ratios 0.005 and 0.3 were modelled in SOLIDWORKS and were given a thickness of 0.001 m in Z

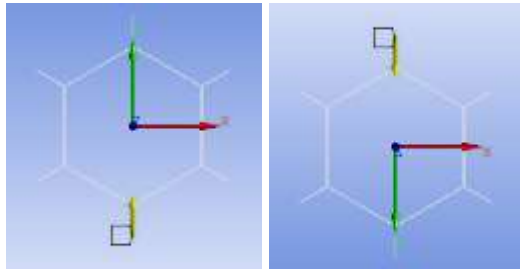
direction in ANSYS Workbench (Static Structural). In both the cells,  $l= 10$  mm, and  $t= 0.05$  mm and  $t= 3$  mm for cells of  $t/l$  ratio 0.005 and 0.3 respectively. The former unit cell denotes a cellular solid which conforms to the relative density requirements of an optimum cellular solid. We already know that cellular solids with relative density ratios greater than 0.3 are simply considered to be solid structures with holes in them. Therefore, for comparison, a unit cell of  $t/l$  ratio 0.3 is taken into consideration. It is important to note here that the relative density ratio of a hexagonal honeycomb is directly proportion to the  $t/l$  ratio, hence, their uses in the text are somewhat similar. Both the unit cells created also have the connecting edges of the adjacent cells up to a length of 0.4 mm. For calculations the entire cells and the outer slant edges are considered. The reason for choosing the latter is that its deformation is also affected by that of the vertical edge connected to it.

S. No.	Property	Value	Unit
1	Density	2770	Kg m-3
2	Isotropic Elasticity (Derive From)		
	Young’s Modulus	7.1E+10	Pa
	Poisson’s Ratio	0.33	
	Bulk Modulus	6.9608E+10	Pa
	Shear Modulus	2.6692E+10	Pa
3	Tensile Yield Strength	2.8E+08	Pa
4	Compressive Yield Strength	2.8E+08	Pa
5	Tensile Ultimate Strength	3.1E+08	Pa
6	Compressive Ultimate Strength	0	Pa

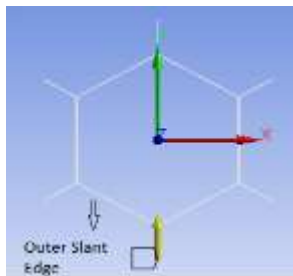
**Table 1:** Properties of Aluminium alloy used to create the honeycomb cells.



**Image 3:** Compressive deformation of value 0.001 m applied on the negative and positive X directions.



**Image 4:** Compressive deformation of value 0.001 m applied on the positive and negative Y directions.

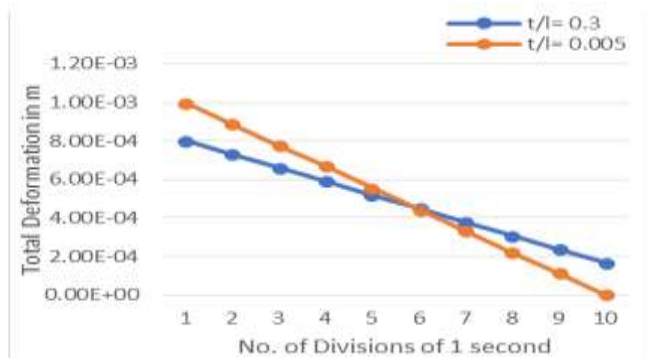


**Image 5:** Outer slant edge in the cell.

## 7. RESULTS AND DISCUSSIONS

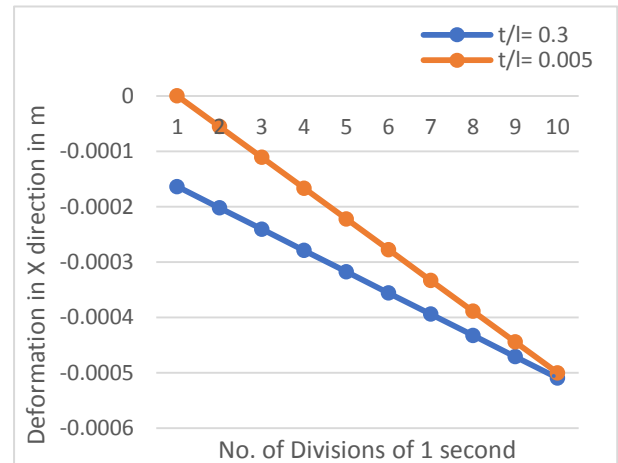
A compressive deformation of 0.001 m is applied in the positive and negative X directions and the total deformation, deformation in X direction and deformation in Y direction of the outer slant edge of regular hexagonal cells of t/l ratios 0.3 and 0.005 are calculated.

The total deformation for both the cells is positive and converges to a common value once. The cell with t/l ratio 0.005 deforms more as it starts its deformation at a closer value to the given deformation of 0.001 m and the calculated value at the end of 1 second is also lower for this cell, meaning that the stretch of deformation for this cell is more.



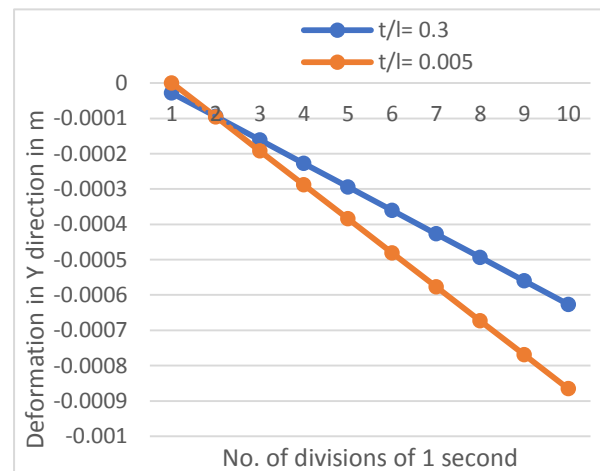
**Chart 1:** Total deformation in m of the outer slant edge of hexagonal cells of t/l ratios 0.3 and 0.005 when a deformation of 0.001 m is applied in positive and negative X directions in 1 second.

The value of deformation in X direction for both the cells is negative. Also, the cell with t/l ratio 0.005, starts its deformation at a higher value than the other cell. But, eventually, at the end of the time period of 1 second, the value of deformation converges to a somewhat similar value for both the cells.



**Chart 2:** Deformation in X direction in m of the outer slant edge of hexagonal cells of t/l ratios 0.3 and 0.005 when a deformation of 0.001 m is applied in positive and negative X directions in 1 second.

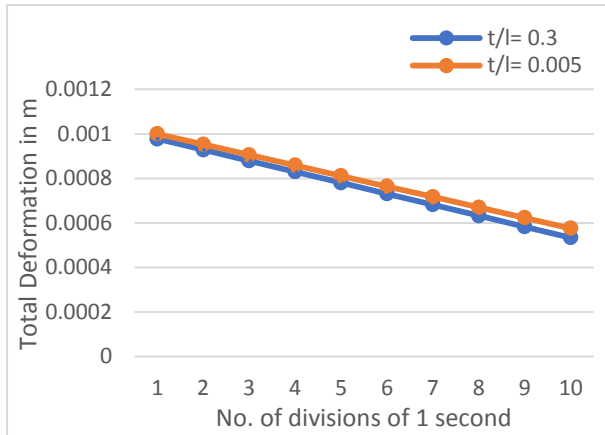
The value of deformation in the Y direction for both the cells is negative and starts at values very close to each other. At the end of 1 second, the cell with t/l ratio 0.005 has a much bigger deformation stretch than the cell with t/l ratio 0.3.



**Chart 3:** Deformation in Y direction in m of the outer slant edge of hexagonal cells of t/l ratios 0.3 and 0.005 when a deformation of 0.001 m is applied in positive and negative X directions in 1 second.

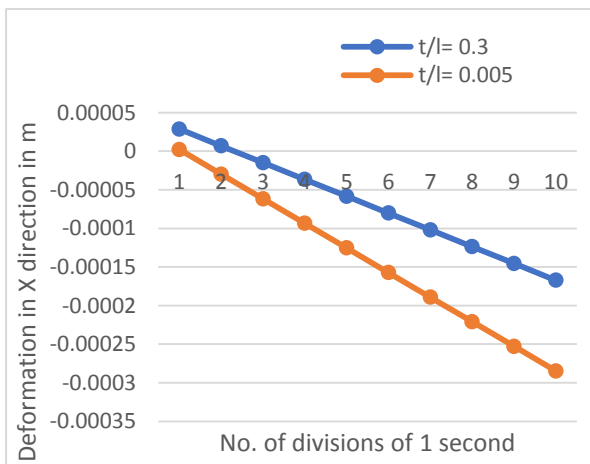
A compressive deformation of 0.001 m is applied in the positive and negative Y directions and the total deformation, deformation in X direction and deformation in Y direction of the outer slant edge of regular hexagonal cells of t/l ratios 0.3 and 0.005 are calculated.

The values of total deformation in both the cells is positive and follows a somewhat same trend.



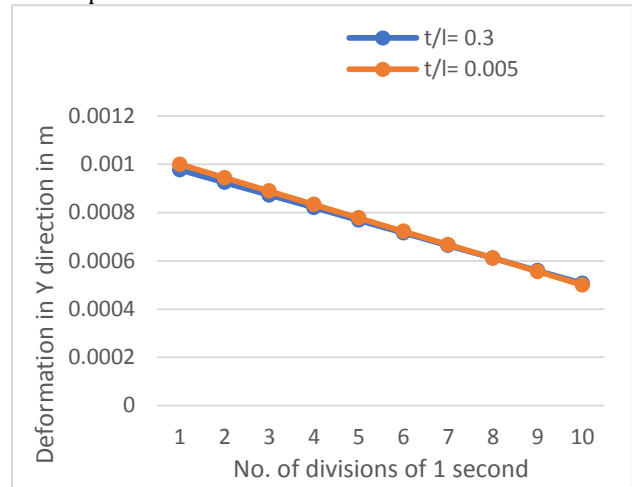
**Chart 4:** Total deformation in m of the outer slant edge of hexagonal cells of t/l ratios 0.3 and 0.005 when a deformation of 0.001 m is applied in positive and negative Y directions in 1 second.

The values of deformation in X direction for both the cells start at a positive value and then reduces to a negative value. The cell with the t/l ratio 0.005 has a much lower value of deformation at the end of 1 second as compared to the cell with t/l ratio 0.3.



**Chart 5:** Deformation in X direction in m of the outer slant edge of hexagonal cells of t/l ratios 0.3 and 0.005 when a deformation of 0.001 m is applied in positive and negative Y directions in 1 second.

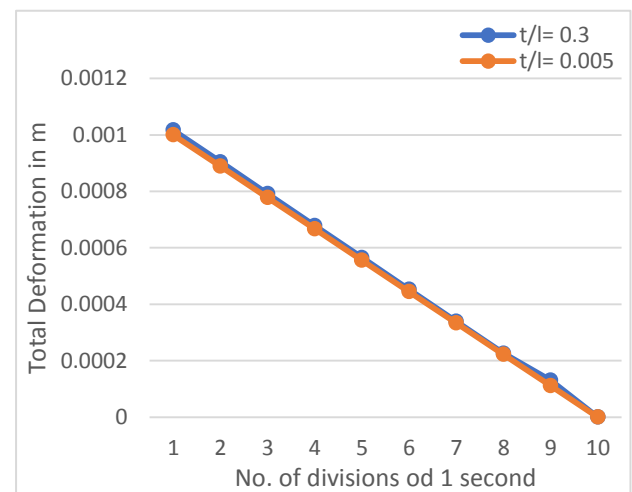
The values of deformation in the Y direction for both the cells are positive and follows a somewhat similar trend.



**Chart 6:** Deformation in Y direction in m of the outer slant edge of hexagonal cells of t/l ratios 0.3 and 0.005 when a deformation of 0.001 m is applied in positive and negative Y directions in 1 second.

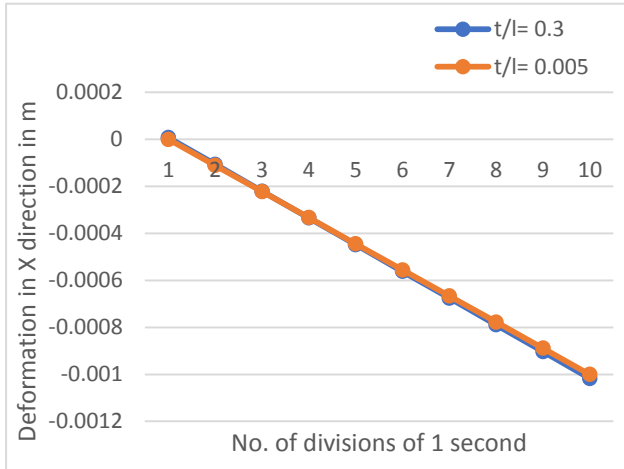
A compressive deformation of 0.001 m is applied in the positive and negative X directions and the total deformation, deformation in X direction and deformation in Y direction of the entire regular hexagonal cells of t/l ratios 0.3 and 0.005 are calculated.

The values of total deformation in both the cells are positive and follow a somewhat similar trend. Also, at the end of 1 second, both the deformation values converge to zero.



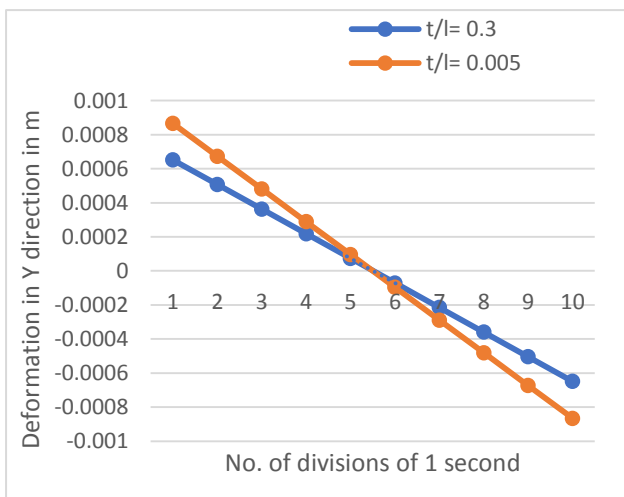
**Chart 7:** Total deformation in m of the entire hexagonal cells of t/l ratios 0.3 and 0.005 when a deformation of 0.001 m is applied in positive and negative X directions in 1 second.

The values of deformation in the X direction for both the cells start at a positive value and at the end of 1 second, becomes negative, while following a similar trend.



**Chart 8:** Deformation in X direction in m of the entire hexagonal cells of t/l ratios 0.3 and 0.005 when a deformation of 0.001 m is applied in positive and negative X directions in 1 second.

The values of deformation in the Y direction for both the cells start at a positive value and ends at a negative value. The stretch of deformation values is more for the cell with t/l ratio 0.005 as compared to the other cell. In the graph, it is observable that the values of deformation for both the cells will have a similar value.

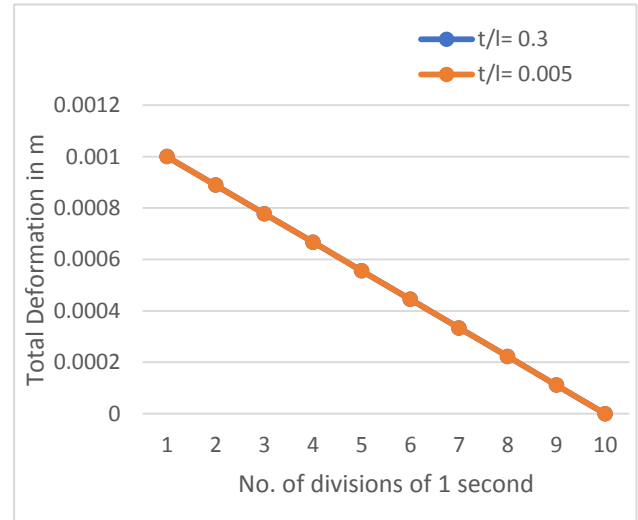


**Chart 9:** Deformation in Y direction in m of the entire hexagonal cells of t/l ratios 0.3 and 0.005 when a deformation of 0.001 m is applied in positive and negative X directions in 1 second.

A compressive deformation of 0.001 m is applied in the positive and negative Y directions and the total deformation, deformation in X direction and deformation

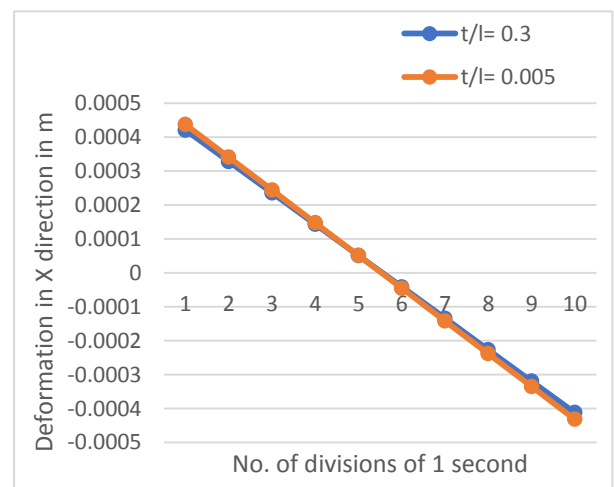
in Y direction of the entire regular hexagonal cells of t/l ratios 0.3 and 0.005 are calculated.

The values of total deformation in both the cells is positive and follows a similar trend. At the end of 1 second, the deformation values end at zero.



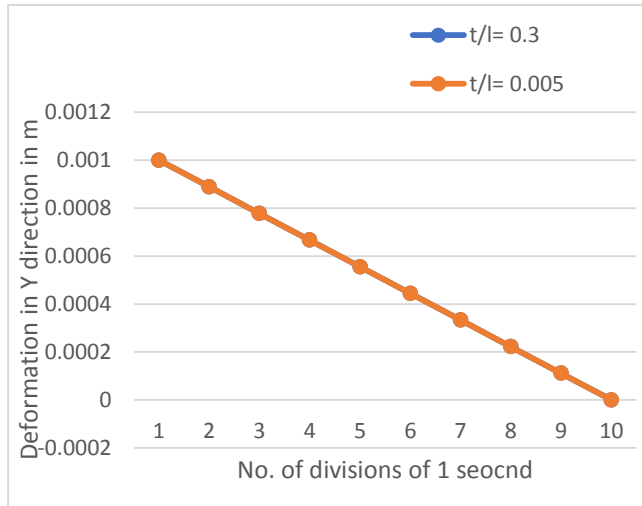
**Chart 10:** Total deformation in m of the entire hexagonal cells of t/l ratios 0.3 and 0.005 when a deformation of 0.001 m is applied in positive and negative Y directions in 1 second.

The values of deformation in X direction of both the cells start at a positive value and at the end of the 1 second becomes negative in value. Both the cells follow a similar trend in the deformation and have values very close to each other.



**Chart 11:** Deformation in X direction in m of the entire hexagonal cells of t/l ratios 0.3 and 0.005 when a deformation of 0.001 m is applied in positive and negative Y directions in 1 second.

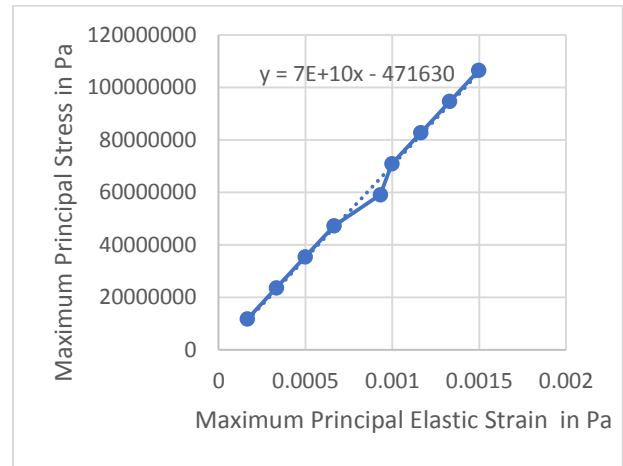
The values of deformation in Y direction for both the cells are positive with the values approaching zero at the end of one second. Both the cells follow a similar trend with values very close to each other.



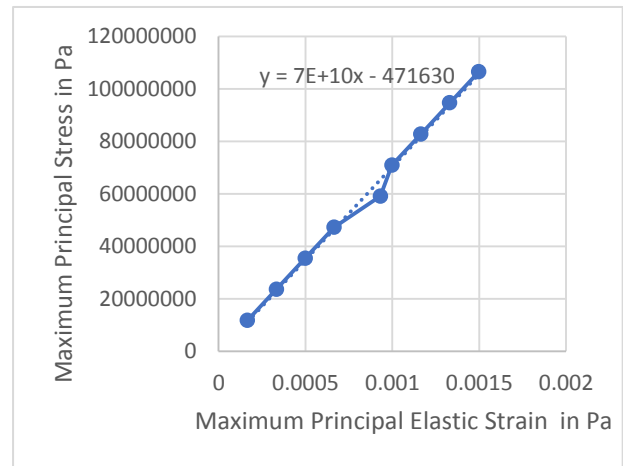
**Chart 12:** Deformation in Y direction in m of the entire hexagonal cells of t/l ratios 0.3 and 0.005 when a deformation of 0.001 m is applied in positive and negative Y directions in 1 second.

A compressive deformation of 0.001 m is applied in the positive and negative X directions and an evaluation of the Maximum Principal Elastic Strain and Maximum Principal Stress is done on the entire cells of t/l ratios 0.005 and 0.3. In both the cells, the graphs constitute of ten values of stress and strain calculated in ten divisions of one second.

The values of stress and strain, for both the cells, decreases with our calculation time and the graph gives us a straight-line trend between stress and strain. The maximum of stress and strain for the latter cell are, approximately, 14.56 times and 15.85 times of that of the former cell, respectively. While the minimum values of stress and strain for the latter cell are, approximately 14.54 and 16.68 times of that of the former cell, respectively.



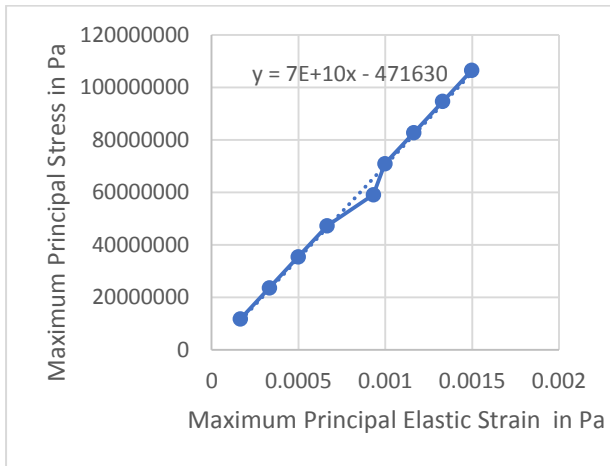
**Chart 13:** Maximum Principal Elastic Strain vs Maximum Principal Stress in Pa for cell of t/l ratio 0.005 when a compressive deformation of 0.001 m is applied in the positive and negative X directions.



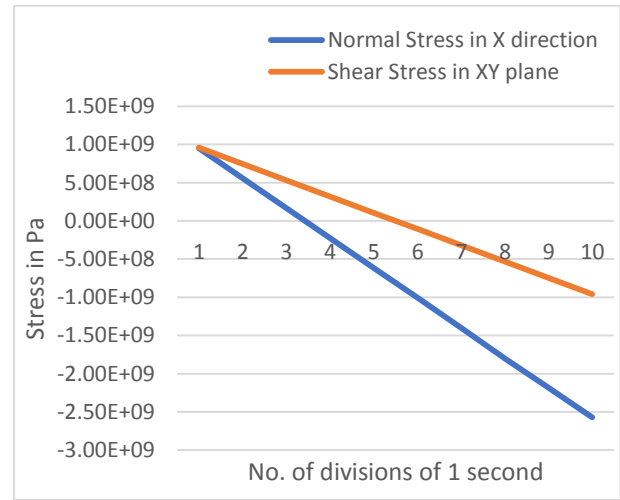
**Chart 14:** Maximum Principal Elastic Strain vs Maximum Principal Stress in Pa for cell of t/l ratio 0.3 when a compressive deformation of 0.001 m is applied in the positive and negative X directions.

A compressive deformation of 0.001 m is applied in the positive and negative Y directions and an evaluation of the Maximum Principal Elastic Strain and Maximum Principal Stress is done on the entire cells of t/l ratios 0.005 and 0.3.

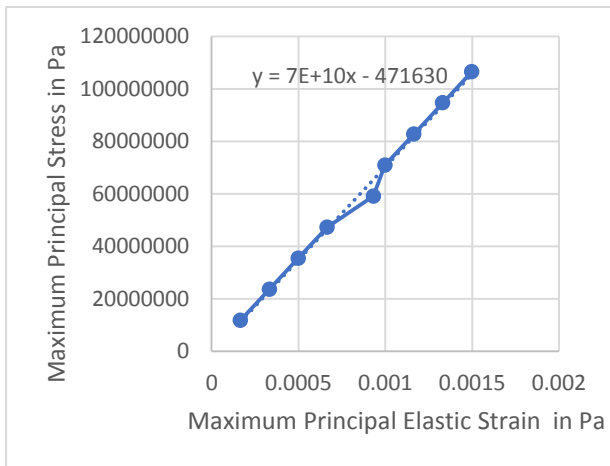
The values of stress and strain, for both cells, decreases and the graph gives us a straight-line trend between stress and strain. The maximum value of stress and strain for the latter are, approximately, 31.67 times and 31.89 times that of the former cell, respectively. While the minimum values of stress and strain for the latter cell are, approximately, 31.74 times and 32.14 times that of the former cell, respectively.



**Chart 15:** Maximum Principal Elastic Strain vs Maximum Principal Stress in Pa for cell of t/l ratio 0.005 when a compressive deformation of 0.001 m is applied in the positive and negative Y directions.



**Chart 17:** Normal stress in X direction and Shear stress in XY plane in Pa for the entire hexagonal cell of t/l ratio 0.3 when a compressive deformation of 0.001 m is applied in the positive and negative X directions.

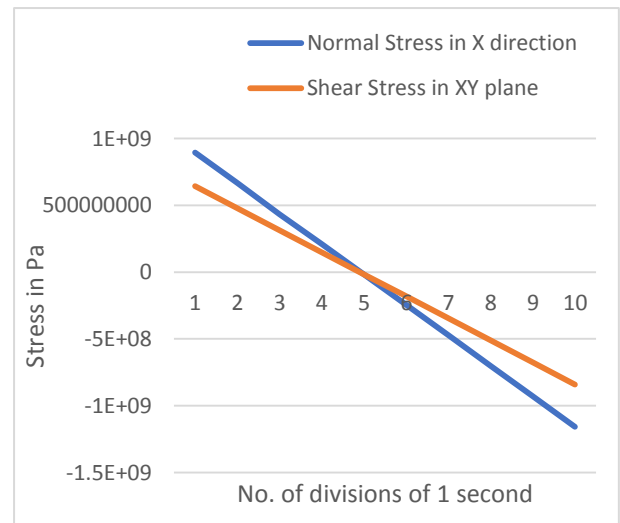


**Chart 16:** Maximum Principal Elastic Strain vs Maximum Principal Stress in Pa for cell of t/l ratio 0.3 when a compressive deformation of 0.001 m is applied in the positive and negative Y directions.

A compressive deformation of 0.001 m is applied in the positive and negative X directions and an evaluation of the Normal Stress in X direction and of Shear Stress in XY plane is done on the entire cell and on the outer slant edge of the cell of t/l ratio 0.3.

When the entire cell is evaluated, it is found that the maximum values of both the stresses is somewhat similar but after the end of one second, the shear stress is greater than the normal stress by 2.7 times.

When the outer slant edge is evaluated, it is found that both the stress values start at some positive values, with the normal stress being greater than the shear stress by 1.4 times. But, as the deformation progresses, the values of stresses become negative and at the end of one second, the value of shear stress becomes 1.4 times greater than that of the normal stress.



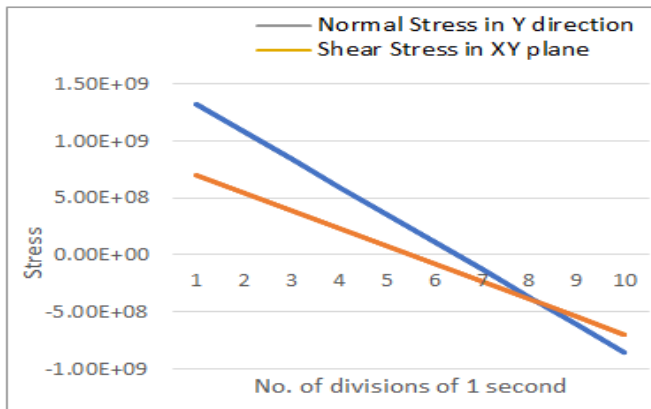
**Chart 18:** Normal stress in X direction and Shear stress in XY plane in Pa for the outer slant edge of the hexagonal cell of t/l ratio 0.3 when a compressive deformation of 0.001 m is applied in the positive and negative X directions.

A compressive deformation of 0.001 m is applied in the positive and negative Y directions and an evaluation of the Normal Stress in X direction and of Shear Stress in XY plane is done on the entire cell and on the outer slant edge



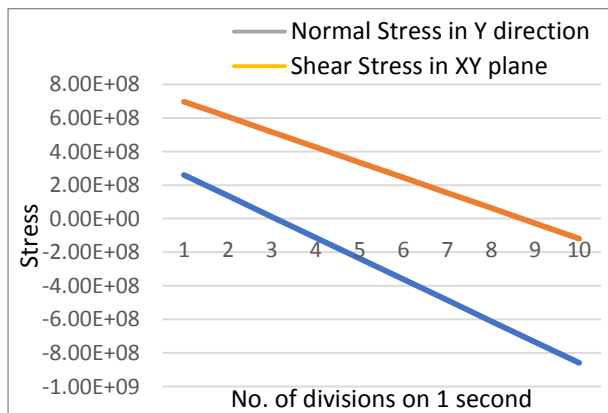
of a cell of t/l ratio 0.3.

When the entire cell is evaluated, it is observed that the both the stress values start at a positive value and then later, become negative. The maximum value of normal stress is, approximately, 1.9 times that of the shear stress, while the minimum value of normal stress is, approximately, 1.23 times less than that of the shear stress.



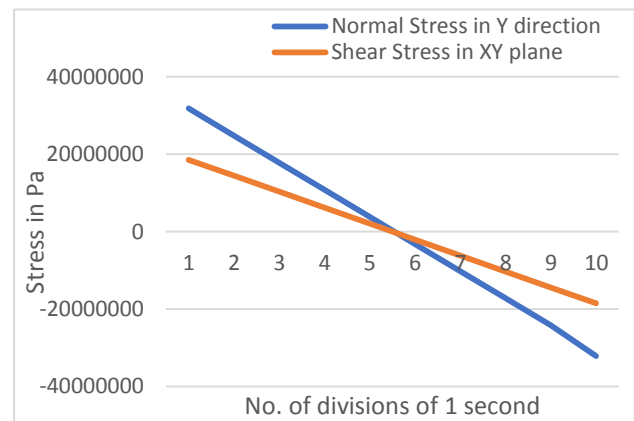
**Chart 19:** Normal stress in X direction and Shear stress in XY plane in Pa for the entire hexagonal cell of t/l ratio 0.3 when a compressive deformation of 0.001 m is applied in the positive and negative Y directions.

When the outer slant edge is evaluated, it is found that the values of both the stresses start at positive, with the maximum shear stress being greater than the maximum normal stress by 2.7 times, and then move onto the negative value, with the minimum value of shear stress being greater than that of the normal stress by 7.26 times.



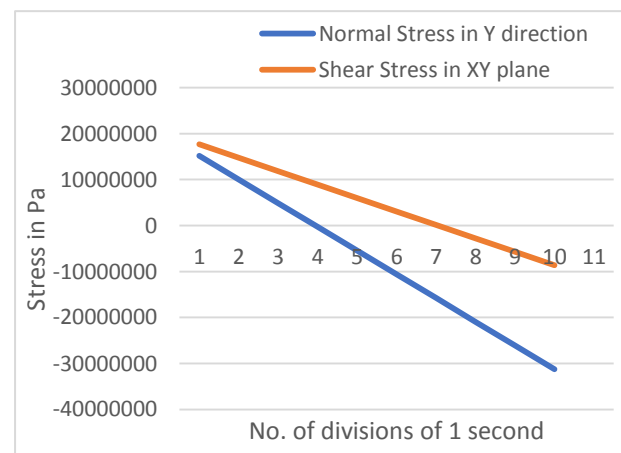
**Chart 20:** Normal stress in X direction and Shear stress in XY plane in Pa for the outer slant edge of the hexagonal cell of t/l ratio 0.3 when a compressive deformation of 0.001 m is applied in the positive and negative Y directions.

A compressive deformation of 0.001 m is applied in the positive and negative X directions and an evaluation of the Normal Stress in X direction and of Shear Stress in XY plane is done on the entire cell and on the outer slant edge of a cell of t/l ratio 0.005. When the entire cell is evaluated, it is found that the maximum value of normal stress is, approximately, 1.7 times greater than that of the shear stress, while the minimum value of normal stress is, approximately, 1.7 times less than that of the shear stress at the end of 1 second.



**Chart 21:** Normal stress in X direction and Shear stress in XY plane in Pa for the entire hexagonal cell of t/l ratio 0.005 when a compressive deformation of 0.001 m is applied in the positive and negative X directions.

When the outer slant edge is evaluated, it is found that the maximum values of the two stress is somewhat same, while the minimum value of normal stress is 3.6 times less than that of the shear stress.



**Chart 22:** Normal stress in X direction and Shear stress in XY plane in Pa for the outer slant edge of the hexagonal cell of t/l ratio 0.005 when a compressive deformation of 0.001 m is applied in the positive and negative X directions.

The deformation of trends of a regular and a commercial hexagonal cell of t/l ratio 0.005 are also evaluated. Here, only the maximum values of deformation are compared. The following results were obtained when the deformation was observed on the entire cell and on the outer slant edge. The deformation was compressive with a value of 0.001 m in the positive and negative X directions:

Deformation in m	Regular Hexagonal Cell	Commercial Hexagonal Cell
X direction	3.07E-09	1.19E-08
Y direction	8.66E-04	8.68E-04

Table 2: Results for entire cell

Deformation in m	Regular Hexagonal Cell	Commercial Hexagonal Cell
X direction	-6.51E-08	-4.55E-08
Y direction	-3.18E-09	-1.74E-08

Table 3: Results for outer slant edge

It is observed that when the entire cell is evaluated, the commercial cell has a greater deformation in X direction as compared to the regular cell in the same direction by 4 times, while the deformation in the Y direction remains same. When the outer slant edge is evaluated, it is found that the commercial cell has a greater deformation in X direction by 1.43 times as compared to the regular cell, while the deformation in the Y direction for the commercial cell is greater than the regular cell by a factor of 18.28 times.

The following results were obtained when the deformation was observed on the entire cell and on the outer slant edge. The deformation was compressive with a value of 0.001 m in the positive and negative Y directions:

Deformation in m	Regular Hexagonal Cell	Commercial Hexagonal Cell
X direction	4.37E-04	3.75E-04
Y direction	0.001	0.001

Table 4: Results for entire cell

Deformation in m	Regular Hexagonal Cell	Commercial Hexagonal Cell
X direction	2.17E-06	9.43E-07
Y direction	0.001	1.00E-03

Table 5: Results for outer slant edge

When the entire cell is evaluated it is found that the deformation of regular cell is greater than that of the commercial cell in X direction by 1.16 times. But when

only the outer slant edge is calculated, it is found that the commercial cell has a greater deformation in the X direction as compared to the regular cell by a factor of 2.3 times. The deformation of both regular and commercial cells in Y direction is same when evaluated for the entire cell or the outer slant edge.

## 8. CONCLUSION

Hexagonal cells with t/l ratios 0.005 show a much proper trend of deformation as compared to the cell of t/l ratio of 0.3, owing to the characteristic property of cellular solids. The commercial honeycombs also show certain unique deformation trends as compared to the regular hexagonal cells, with the former cell almost always depicting a much higher deformation.

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