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ACOUSTIC PERFORMANCE OF REITERATED HIERARCHICAL HONEYCOMB STRUCTURES

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ACOUSTIC PERFORMANCE OF REITERATED HIERARCHICAL HONEYCOMB STRUCTURES

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ABSTRACT

Sandwich panels constructed from honeycomb structures have been found to reduce sound transmission and improve vibration isolation. In this work, reiterated hierarchical honeycomb structures have been modeled for the core in sandwich panels and studied for sound transmission properties using finite element analysis. Several honeycomb unit cell geometries are considered, including, regular hexagonal, auxetic with properties of negative Poisson's ratio, and different reiterated hierarchical structures. Previous studies have shown that auxetic honeycomb structures exhibit improved sound transmission loss compared to regular honeycomb sandwich panels. Two different orientations of the honeycomb unit cell geometry have been studied, namely, the zigzag and armchair configurations, which are, rotated 90 degrees. Both regular and auxetic honeycombs have been used in both these configurations. The finite element model of the panels are used to extract natural frequencies and mode shapes and to perform steady state frequency response dynamic analysis up to 1000 Hz.

The transmitted sound pressure levels on the surface of each structure is extracted and compared to study the influence of the reiterated hierarchy on sound transmission characteristics. The influence of corner reinforcement constructed by subtracting interior high-level hierarchical structure except at the vertices of the underlying lower-level honeycomb unit cell was also studied. Furthermore, a study was conducted to quantify the effect of changing the ratio of cell-wall thickness between various levels of hierarchy. Special focus on the limiting case of level-1 hierarchy with zero level-0 thickness is also

studied. In all cases, the total mass was kept constant in order to isolate only stiffness and mass distribution effects.

The results show that introduction of reiterated hierarchy in level-1 structures reduced the sound transmission of honeycomb sandwich panels compared to parent level-0 geometry. Results also showed that the corner reinforcement does not influence the sound transmission characteristics significantly, but does change the stiffness of the structure. For regular hexagonal honeycombs, changing the ratio of thickness between various levels of hierarchy did not affect the sound transmission significantly but made the structure stiffer when the ratio was increased, and reduced the stiffness when the ratio was decreased. For auxetic honeycomb structure, increasing the ratio made the structure less stiff, but reducing the ratio did not change the stiffness significantly.

DEDICATION

I dedicate this thesis to my mother and all my other family members and friends.

ACKNOWLEDGMENTS

I would like to thank Dr. Lonny Thomson for his guidance and support throughout my Master's degree program which has been invaluable. I would also like to thank my committee members Dr. Gang Li and Dr. Joshua Summers for their timely inputs and support.

Last but not least I would also like to thank my research group mates and other friends for their encouragement and making my stay at Clemson a memorable one.

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CHAPTER-1

INTRODUCTION

Metamaterials are engineered material with properties different from their constituent base material. They can be designed for many purposes such as to alter the wavelength of light, electromagnetic radiation or amplitude of sound transmitted by modifying their shape, orientation, size, geometry and/or arrangement. Acoustic metamaterials are designed to control sound waves. They usually gain their properties from structure rather than composition. Many different structures have been proposed including using the inclusion of small inhomogeneities to enact effective macroscopic behavior [36, 37].

Honeycomb sandwich panels have been in use since 1914 for structural purposes. [38] Honeycombs are cellular metamaterials which can be controlled to give effective material properties by changing the core geometry and cell configuration. Honeycombs are two dimensional cellular structures which have been used for structural protection, impact energy absorption and thermal isolation purpose. The static mechanical properties of honeycomb core are well defined by Gibson and Ashby's cellular material theory [16]. Honeycomb sandwich panel are made of honeycomb core sandwiched between two thin face plates. They are found to posses high specific strength defined as strength to weight ratio and this property has made them indispensible in the aerospace industry where lightweight construction is usually critical. Another important reason for using honeycomb sandwich structures in automobile and aerospace structure is the demand for

reduced fuel consumption using lightweight construction. There have been many studies on the core geometry and orientation of honeycomb sandwich panels in the past and their influence on the sound transmission loss. An area, which has not been explored fully in the past, is the effect of the honeycomb cell wall thickness and its control on the sound transmission property.

The main objective of this work is to study the effect of reiterated honeycomb core geometry, the influence of corner reinforcements, and the effect of ratio of thickness of various levels of hierarchy. After defining and discussing previous applications of these reiterated honeycomb structures, the objectives of the thesis will be described in further detail at the end of Chapter.

1.1 Hierarchical Honeycomb Structures

Hierarchical cellular structures prevail in nature in many cases as basic building blocks such as cell and tissues up to entire ecosystems [46]. They are integral to the survival of the many biological systems and in many cases they provide structural reinforcement and negate the effect of flaws in the structures. This property of hierarchical structures has been taken advantage by engineers. Hierarchical structures have been used in civil and mechanical structures for their superior strength; for example the Eiffel tower in Paris, France which is designed using a third order hierarchical structure [39]. The organization of the cells in hierarchy is the most important factor influencing the strength of the structure. Tailorable and superior mechanical properties

are obtainable using hierarchical organization. The overall performance is ultimately governed by the length scales and levels of hierarchy. There has been studies done in the past which showed that hierarchy in honeycomb sandwich panel cores can result in better performing failure strength and fracture toughness with lighter weights [31].

1.2 Sound Pressure Level

Sound pressure is a pressure disturbance in the atmosphere which is influenced by the surroundings, strength of the source and the also the distance from the source to receiver. Sound pressure level (SPL) or acoustic pressure level is defined as the logarithmic measure of the effective sound pressure of a sound relative to a reference value. This reference value is usually chosen to be 20μPa which is the threshold for human hearing. The sound pressure level can be calculated in Decibels as $20\log_{10}(p/p_o)$, where p is the root mean square sound pressure and p_o is the reference sound pressure. In this work the sound pressure level is used to study the acoustical properties of hierarchical honeycomb sandwich panels, though the sound transmission loss is the most commonly used parameter in the study of acoustical properties of honeycomb sandwich panels. A reduction in sound pressure level can be result of either sound absorption or sound insulation. In this work we study the parameters, which influence the sound insulation characteristics of honeycomb sandwich panel.

1.3 Sound Transmission Loss

Sound transmission loss (STL) is the most common metric for measuring sound absorption. The sound transmission loss of a panel depends on the geometry, frequency and material. The STL curve has four basic regions .The first region is predominantly controlled by the stiffness of the panel. This region contains the lowest frequency up to the first natural frequency. Factors like damping and mass have little influence in this region. Followed by the stiffness controlled region is the resonance controlled region which is predominantly controlled by the natural resonance of the panel. The resonant frequency is a frequency at which the panel vibrates the maximum and it depends on the material, size, shape and mounting conditions. Because of this high sound transmission in this region there are several dips in STL curve representing the very low loss in sound transmission [29].

Followed by the resonant controlled region is the mass controlled region .In this region the response is very much dependent on the mass. The curve follows a 6 dB/ octave slope i.e. doubling the mass or frequency result in a 6 dB increase in the sound transmission loss. This appears to be an important region in sound insulation.

Beyond the mass law region is the coincidence region .In this region is there is a dip in the STL curve resulting due to the efficient transfer of sound from the incident side to the transmitted side. This is primarily due to the coincidence effect i.e. matching of the incident and bending wave in the partition. The coincidence region begins from critical frequency given by the formula given below.

1.4 Literature Survey

There has been several studies in the past regarding honeycomb sandwich panels and hierarchical honeycombs. Fan, et al. studied the mechanical properties of 2D hierarchical cellular structures with sandwich walls and proved that hierarchical structures performed better compared to solid wall cellular materials. Their study concluded that the sandwich strut enhanced the Euler buckling strength and stiffness. It also enhances the plastic collapse strength, the brittle failure strength and the fracture toughness of the hierarchical honeycombs. The hierarchical honeycomb was found to be much more resistant to cracks and insensitive to wavy imperfection of cell walls. They were also found to be enhances anti-buckling, anti-crushing and anti-impact properties. Another important finding was that the hierarchy does not influence the stiffness [31].

Taylor and Smith had studied the effect of introducing hierarchy on the in plane elastic properties of honeycomb .The parameters varied in the work included the geometry of the super- and sub-structure, the combination of different geometries at different hierarchical levels, the proportion and distribution of mass between hierarchical levels, the Poisson's ratio of the different hierarchical levels. Their study showed that it is possible to improve the in plane modulus by 175 % by using functionally graded hierarchies in comparison to a similar density first order hierarchy hexagonal honeycomb [7].

Amin, et al. investigated the mechanical behavior of two dimensional hierarchical honeycomb structures using analytical, numerical and experimental methods. Their work gives an insight into the role of structural organization and hierarchy in controlling the

mechanical behavior of material. Their honeycombs were constructed by replacing every three edge vertex of a regular honeycomb lattice with a smaller hexagon. They proved that a broad variety of elastic properties can be achieved by tailoring the structural organization hierarchy and the two dimension ratio. They also proposed that future optimization is possible by varying the thickness of the hierarchically introduced cell wall i.e. varying the relative distribution of mass between different hierarchy levels [4].

Amin, et al. again investigated the dynamic crushing of two dimensional honeycombs with both regular and irregular arrangement using finite element analysis. They identified several deformation modes for the honeycombs subjected to dynamic crushing. They studied the role of dynamic effects on the energy absorption, impact resistance and the effect of irregularities. Their results show that introducing a density gradient can significantly change the deformation mode and energy absorption of cellular material under both low and high crushing velocities [5].

So far the past work on honeycombs structures and their influence on the mechanical properties were discussed. The sound transmission properties of sandwich panels were explored initially by Kurtze and Watters. They used a three layer sandwich plate and studied its influence on the sound transmission and damping characteristics. The core material had a very high static to dynamic stiffness ratio. They found that by choosing a core material which results in plateau speed which is less than the speed of sound in air, it is possible to shift the coincident frequency of the panel towards the higher frequency. By this method we can create a panel which obeys the mass law in the entire frequency range of interest [25].

The work done by Ford, et al. involved studying both flexural and dilatory modes of vibration for a model which had rigid polyurethane foam core. Their work mostly concentrated on comparing experimental results with theoretical values. Their work concluded that the low frequency dips were a result of flexural modes of vibration and the higher frequency dips were attributed to the dilatational modes of vibration [26].

Smolensk and Krokosky tried to compare theoretical analysis of an elastic sandwich panel based on theory of dilatory sound transmission with experimental observation. Their concentration was primarily on panels using lightweight foamed core materials. They concluded that the susceptibility of the lightweight sandwich panel cores to dilatational modes of vibration is the reason for the undesirable coincidence and resonance depression in the sound transmission spectra. It was also proved that the flexural mode of vibration was insensitive to changes in core compressibility and thickness, whereas the dilatational vibrations were highly sensitive to these parameters [33]. It is to be noted that so far none of the work aimed at calculating the sound transmission loss of the sandwich plate [25, 26, and 33].

Dym and Lang were the first to obtain analytical expression for impedance and sound transmission loss for sandwich panels using variational formulation of consistent plate theory. They showed that both the symmetric and anti-symmetric resonance of a panel had a strong relation with its length. And also that for a large panel the lowest frequency mode is always due to the anti-symmetric mode and the lowest frequency mode for such a panel is not influenced by the dilatational term [34]. They later extended their research from symmetric sandwich panels to asymmetric sandwich panels and found

that for constant mass panels with asymmetric configuration had poor acoustical performance than panel with symmetric configuration [44].

Moore and Lyon developed analytical models for transmission loss for orthotropic core with a low compression stiffness and high shear stiffness. They predicted that for symmetric modes, coincidence occurs near the double wall resonance frequency. The symmetric modes were characterized by the stiffness of the core and mass of the face sheets, whereas the antisymmetric modes were characterized by the shear deformation of the core. Their results were in good agreement with their predictions. And also they designed a procedure to improve transmission loss by shifting the double wall resonance below the frequency band of interest and limit the shear stiffness of the core to shift the onset of bending wave coincidence. They also found that reducing the thickness of the core without changing material properties results in increasing the stiffness of the core [35].

Thamburaj and Sun [50] tried to optimize sound transmission loss across anisotropic sandwich beam and found that anisotropic cores created a increase in sound transmission loss when compared to isotropic core. So far the work discussed had studied the influence of various mode shapes of isotropic, anisotropic and orthotropic core. on the sound transmission property Zhou and Crocker [12] had studied the forced vibration of asymmetric sandwich panels made up of graphite fiber ace sheet and foam filled honeycomb cores, using wave impedance analysis. They found that boundary element analysis is much suited for transmission loss measurement influenced by resonance behavior and statistical energy analysis is much suited for higher frequencies. Their

results were in agreement with Dym and Lang's [44] prediction for asymmetric sandwich panels with isotropic materials. Also for the panels studied the sound transmission loss was found to be caused by antisymmetric motion of panel.

Most of the works on sound transmission loss, discussed so far were interested in higher frequency range. One of the latest works in this field has used a hybrid analytical/ FEM method HAFEM, where finite element approximations are made in the thickness direction, while analytical solutions are assumed in the plane direction [48]. This method claims to have reduced the analysis time drastically.

Dag Lukkassen worked on reiterated honeycomb with different micro-levels. He found the upper and lower bounds using the homogenization theory for effective thermal properties. And those bounds turned out to be close for higher values of reiteration number. His work also points out that this limit is optimal within the class of two phase structures with prescribed volume fraction. He also states that for the reiterated cell-structures the bounds were obtained by reiterating the estimates from his previous work but that these estimates were useless in the case of reiterated honeycombs [28,49].

1.5 Motivation for the Study

This study was initiated to check the possibility of utilizing models developed from homogenization theory. Bruggeman introduced reiterated homogenization on the physical level in the late 1930's. The theory has been mathematically justified by Bensoussan, Lions and Papanicolaou [28, 41]. We are very much interested in the recent models developed by this theory. Some reiterated models developed by theory are shown

in Figure 1.1, 1.2 and 1.3. In this study a similar model of reiterated honeycomb is used as unit cell for creation of sandwich core and studied for various acoustical properties of honeycomb sandwich panels. It is worthwhile to note that the models used have varying thickness for each level of hierarchy. From our literature survey we already know that there has not been any previous study on the effect of thickness for various level of hierarchy. The Figure shown in Figure 1.3 is a reiterated honeycomb structure, which is found to be nearly optimal for effective conductivity.

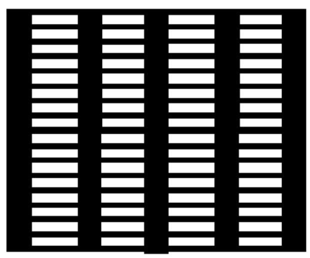


Figure1.1: Laminate structure of rank 2 [27]

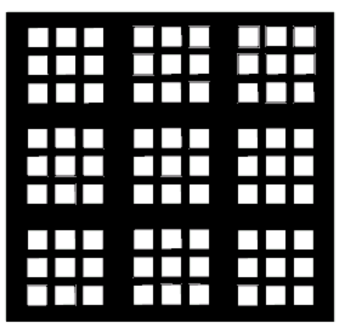


Figure 1.2: Reiterated cube structure [27]

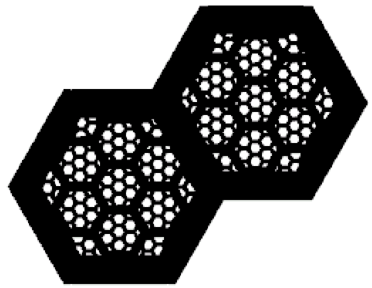


Figure 1.3: Iterated hexagonal honeycomb. [27]

1.6 Objective and Thesis Outline

The primary objectives of this thesis are to study:

1. ***The influence of hierarchy on the sound transmission property***. To study the influence of reiterated hierarchical structures as core geometry for sandwich panels on the sound transmission properties. The core geometry primarily varies upon different hierarchical levels. Both the regular and auxetic honeycombs are studied using finite element models developed in Abaqus in two different configurations. The two configurations primarily vary with respect to the orientation of the honeycombs.
2. ***The effect of hexagonal and rhombic corner reinforcement on the sound transmission property.*** The effect of corner reinforcement which are formed due to the hierarchy level differences and repetition of unit cells of different hierarchy. The corner reinforcement is in the shape of hexagon for regular honeycombs and in the shape of rhombus in the case of auxetic honeycombs.

3. ***The effect of the ratio of thickness of cells belonging to various levels of hierarchy on the sound transmission property***. The effect of the ratio of thickness of unit cells belonging to various levels of hierarchy. Study the ratio of thickness of cells belonging to level-1 hierarchy over thickness of cell belonging to level-0 hierarchy honeycombs.

All the studies are carried with models of equal mass. The mass is maintained constant as it has a major influence on the sound transmission property in the resonance controlled region. All the dynamic studies are done in the stiffness and resonance controlled region.

An outline of the organization is given below.

- **Chapter 1:** Gives a brief introduction to metamaterials, hierarchical honeycombs and their advantages. Then a brief introduction to the concepts involved in carrying out the study is given, followed by the background of previous research and reasons for carrying out the current study. A brief outline of the thesis is also discussed in this chapter.
- **Chapter 2:** This chapter deals with geometry of the honeycombs and their effective properties. The process of creating various levels of hierarchy in the honeycombs is also explained. A comparison of bending stiffness of regular and auxetic, single layered and multilayered honeycomb structures used are made based on analytical results.
- **Chapter 3:** This chapter explains how the honeycomb core is modeled and how the model is setup in Abaqus. The procedure for performing the steady state

dynamic analysis is explained in detail. It also explains how the sound pressure level and sound transmission loss is being extracted from the analysis. A mesh convergence study for the air domain and the sandwich panel is conducted to validate the accuracy of the results.

- **Chapter 4:** The results of natural frequency extraction procedure are discussed in detail. The various mode shapes are also presented. Comparison studies are performed using the natural frequencies and their inference is discussed.
- **Chapter 5:** The results of the analysis performed on zigzag and armchair configuration are discussed in detail this chapter. Various comparisons and the inference from these compassions are also included.
- **Chapter 6:** This chapter concludes the present work and gives a summary of the work done so far. Possible future work has also been discussed.

CHAPTER-2

CONSTRUCTION AND PROPERTIES OF HONEYCOMB SANDWICH PANELS

The studies conducted in this work are primarily carried out using in-plane honeycomb sandwich panel configuration. It is to be noted that not all of the previous work involving studies on the mechanical properties of honeycomb sandwich panels employed in plane honeycomb sandwich panel configuration. The in-plane stiffness and strength are lowest as the stresses in the plane make the cell walls bend. Whereas as the out of plane stiffness and strength are generally higher as they requires the extension and compression of the cell wall [3]. The sandwich panels, which are used in the out of plane loading configuration, are generally short in the direction of loading to avoid buckling.

2.1 Honeycomb Sandwich Panel

The honeycomb sandwich panel used in the analysis consists of two face sheets and a honeycomb core. The core is made up of repeating and non-overlapping unit cells. The various unit cells used are discussed in later sections.

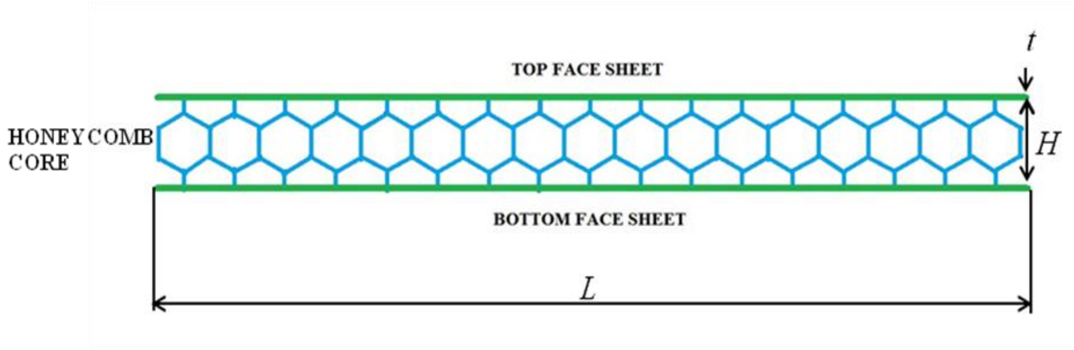


Figure 2.1: Honeycomb sandwich panel parameters

In this study we use two different configurations, the zigzag and armchair configuration. In the zigzag configuration the regular honeycomb is inverted 90^{o} as shown in Figure 2.3 and in the armchair configuration the regular honeycomb is used as shown in the Figure 2.2. The honeycombs have an internal angle $\theta = 30°$ for the regular honeycomb and an internal angle of $\theta = -30°$ for the auxetic honeycomb. These specific internal angles make the length equal to height for regular honeycombs and for auxetic honeycombs the height is equal to twice the length. Since we are using a constant θ and have already decide the length of the panel, the number of unit cells are calculated using parameter Lx shown in Figures 2.2 and 2.3

For armchair configuration cells $Lx = 2l\cos\theta$ and $Ly = 2(h + l\sin\theta)$ where l is the length of the honeycomb, h is the height and $\theta = 30°$, the internal angle as shown in Figure 2.2.

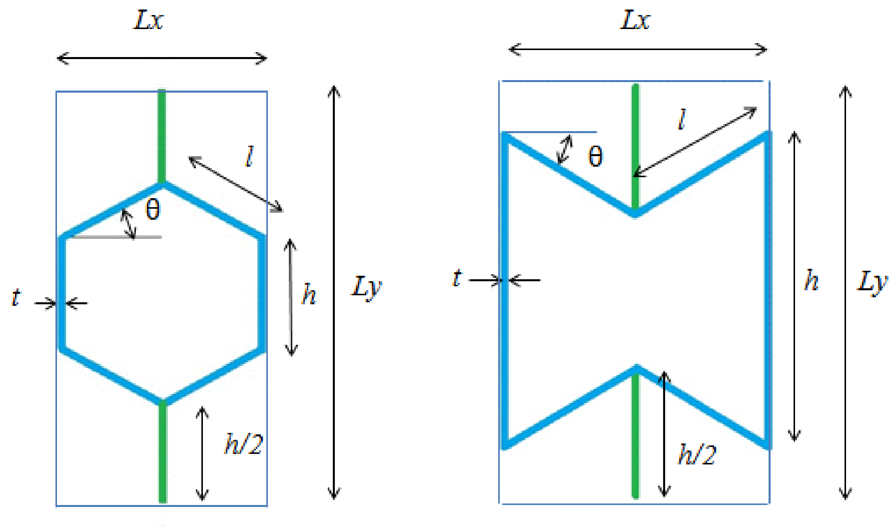


Figure 2.2: Regular honeycomb and Auxetic honeycomb cell orientation for armchair configuration

For the zigzag configuration cells $Lx = h(2\sin\theta + 1)$ and $Ly = 2h\cos\theta$ where h is the height of the honeycomb and $\theta = 30°$ as shown in Figure 2.3. But this value of Lx cannot be used for calculating the number of unit cell as this configuration couples two unit cells in a particular order as shown in Figure 2.4. So the overall length of the unit cell is calculated as Lx +w, where w is the width as shown in Figure 2.3.

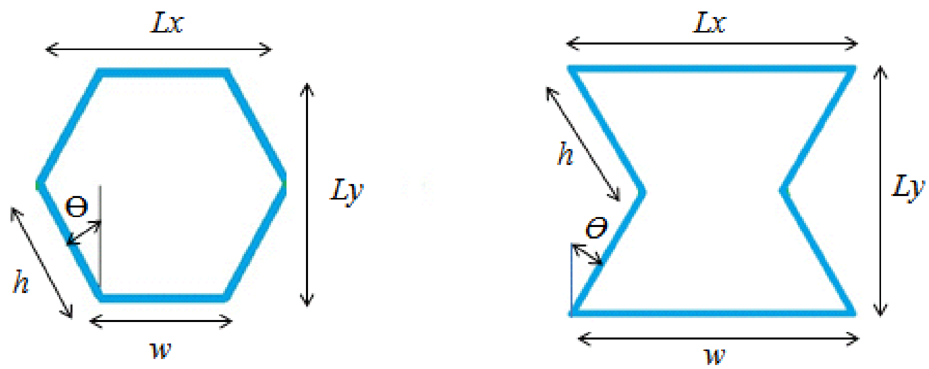


Figure 2.3: Regular honeycomb and Auxetic honeycomb cell orientation for zigzag configuration

2.2 Model Setup for Zigzag Configuration Honeycomb Structure

2.2.1 Construction of Level-0 Structures

The overall length of the panels L= 2.016608 m and the height H=0.0866 m. The zigzag configuration is considered first. In order to compensate for the additional length of the honeycomb edge which was protruding from the face sheet in the zigzag orientation an additional 0.016608m was added to 2 meter length which was originally used in previous studies. This additional 0.016608 was added to all models of both configurations in order to maintain the length constant. In the zigzag configuration the regular and auxetic honeycomb unit cells are reoriented as shown in Figure 2.3 This will be referred to as Level-0 Honeycomb (L-0 HC). The zigzag configuration models couple two consecutive honeycombs and use them as one unit cell in the model generation process. So this geometry in Figure 2.4 is repeated to obtain the length of 2.016608 m.

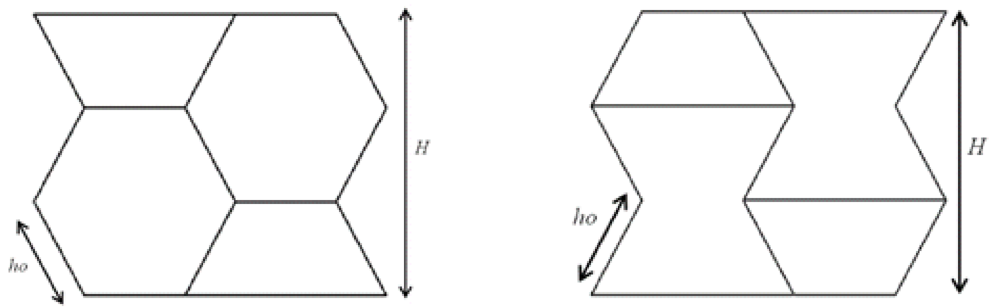


Figure 2.4 Construction of level-0 regular and auxetic unit cell

The level-0 honeycomb is created using simple geometric relations

$$H = 3h_o \cos\theta \quad \textbf{(2.1)}$$

where H is the height of the core, θ is 30° for the regular honeycomb and –30° for auxetic honeycombs and h_o is height of a level-0 honeycomb.

2.2.2 Construction of Level-1 Structures

The next level of the hierarchical honeycomb is created by placing seven smaller regular honeycombs inside the each level-0 honeycomb for the regular honeycomb model. For the auxetic model the level-1 honeycomb is created by placement of seven smaller auxetic honeycombs in same order as the regular honeycomb.

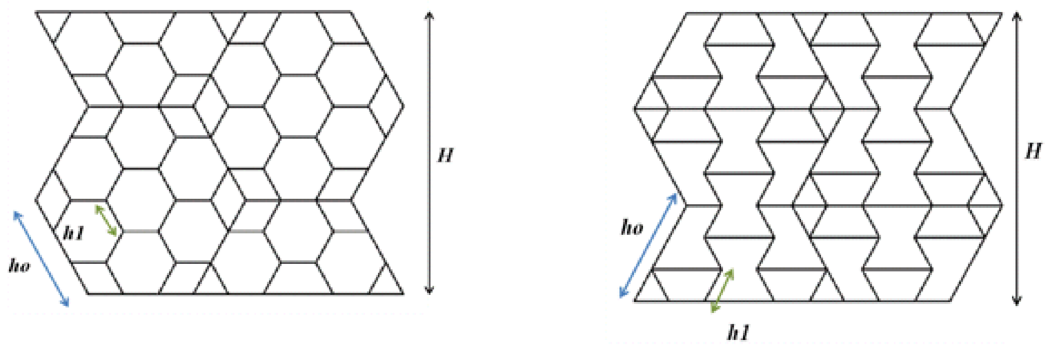


Figure 2.5: Construction of level-1 regular and auxetic unit cell

The level-1 is created such that there are three smaller honeycombs along the direction of each face of the each level-0 cell of honeycomb, thus $h_1 = h_0 / 3$ also $3h_1 = h_0$. Since the honeycombs have an internal angle of 30^o, the length and height of honeycomb is equal. Therefore the height of the level-1 honeycomb is calculated using the geometric relations as

$$9h_1 = 3h_0 \tag{2.2}$$

$$h_1 = \frac{h_0}{3} \tag{2.3}$$

$$H = 9h_1 \cos\theta \tag{2.4}$$

where H is the height of the core, h_1 is the height of the level-1 honeycomb cell as shown in Figure 2.5 and θ is 30^o.

2.2.3 Construction of Level-2 Structures

Though level-2 hierarchical honeycombs are not discussed extensively, one model was created to check the impact on the acoustical properties. This model of level-2 hierarchical honeycomb has seven smaller honeycombs within each of the level-1 hierarchical honeycombs. And in a similar fashion the length of the level-2 honeycombs can be calculated by using the given formula based on geometric relations

$$h_2 = h_1 / 3 = h_0 / 9 . \quad \textbf{(2.5)}$$

Therefore

$$H = 27 h_2 cos\theta \ . \quad \textbf{(2.6)}$$

The resulting unit cell structure for level-2 is shown in Figure 2.7 c)

2.2.4 Construction of Corner Reinforced and Level-1* Structures

The corner reinforced honeycomb is created by removing the level-1 honeycombs in the center of the level-0 honeycombs, except the corner honeycombs. For regular honeycombs hexagonal corner reinforcement is created by this process whereas rhombic corner reinforcement is created for auxetic structures. This can be clearly seen in Figure 2.7 d) and in Figure 2.10 c).

The Level-1* structure is created by removing the entire level-0 honeycomb from the level-1 model for regular honeycombs. In the case of auxetic honeycombs removing the entire level-0 structure resulted in isolation of honeycombs belonging to two consecutive cells .In order to create a continuous structure three links were not removed This can be seen in Figure 2.6. The level-0 structure is represented in red.

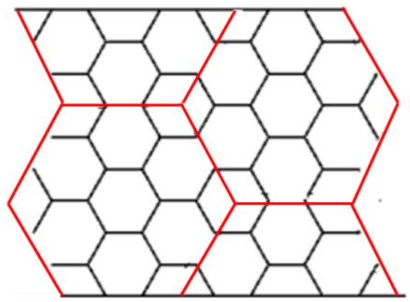


Figure 2.6 Level-1* structure creation

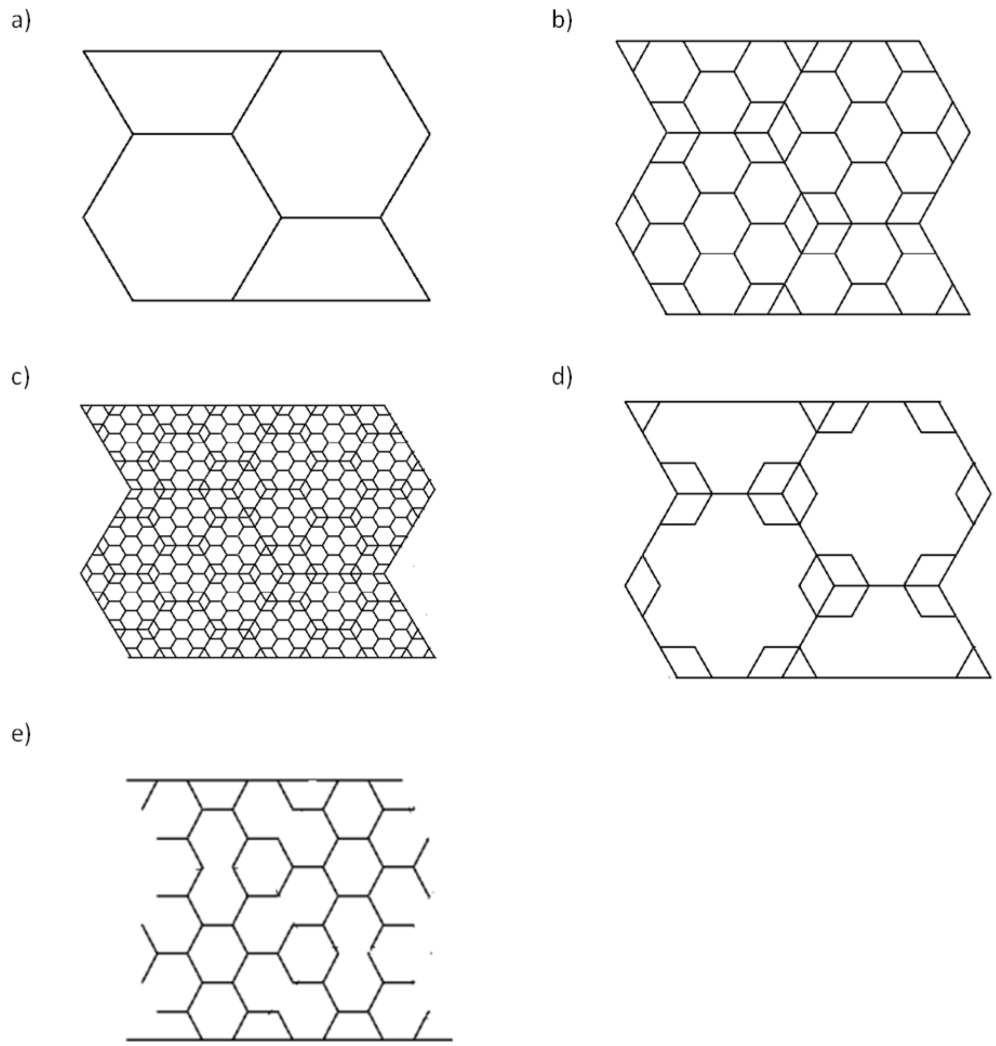


Figure 2.7: Zigzag configuration regular honeycomb unit cells

a) Level-0

b) Level-1

c) Level-2

d) Corner reinforced

g) Level-1*

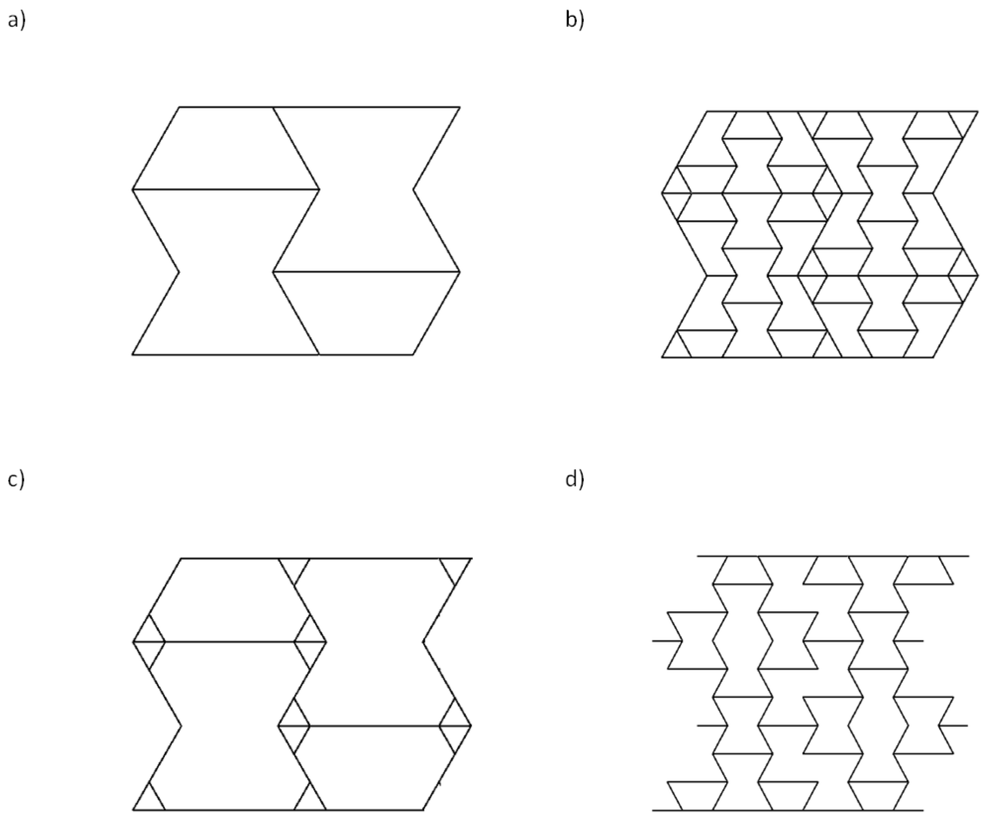


Figure 2.8: Zigzag configuration auxetic honeycomb unit cells

a) Level-0

b) Level-1

c) Corner reinforced honeycomb

d) Level-1*

2.2.5 Construction of Multilayered Structures

Only two multilayered structures are studied, the level-0 and level-1 structure. The multilayered structures for zigzag configuration are created by adding half honeycomb on top of the single layer structures. The geometric relation used for calculation of length of honeycomb is given as

$$H = 4h_0 \cos\theta \qquad \textbf{(2.7)}$$

where H is the height of the core, θ is 30° for the regular honeycomb and –30° for auxetic honeycombs and h_0 is height of a level-0 honeycomb as shown in Figure 2.5. The resulting multilayer structures are presented in Figure 2.9 a) and b) and Figure 2.10 a) and b). The length of level-1 structures are the same value which were calculated for the level-1 single layer structures.

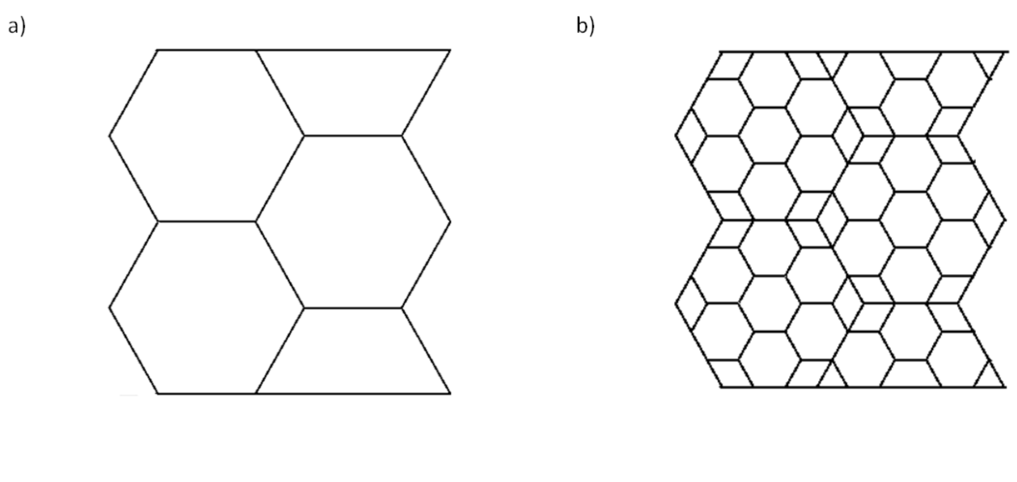


Figure 2.9: Zigzag configuration multilayer regular honeycomb unit cells a) Level-0 b) Level-1

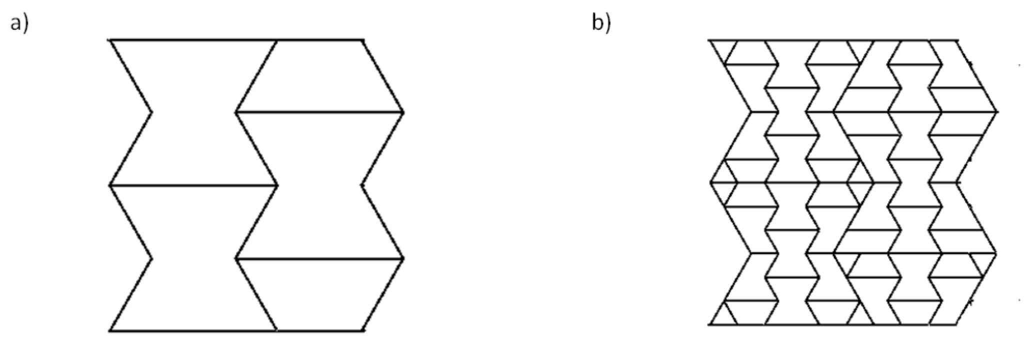


Figure 2.10: Zigzag configuration multilayer auxetic honeycomb unit cells a) Level-0 b) Level-1

2.2.6 Sandwich Panels of Various Core Geometries

The Figure 2.11 and 2.12 gives a clear idea about the panels used in the study. As discussed earlier all panels have a constant length. The zigzag configuration single layered regular and auxetic level-0 honeycombs have 40 cells in the length direction, whereas the multilayered regular and auxetic structures have 54 cells in the length direction.

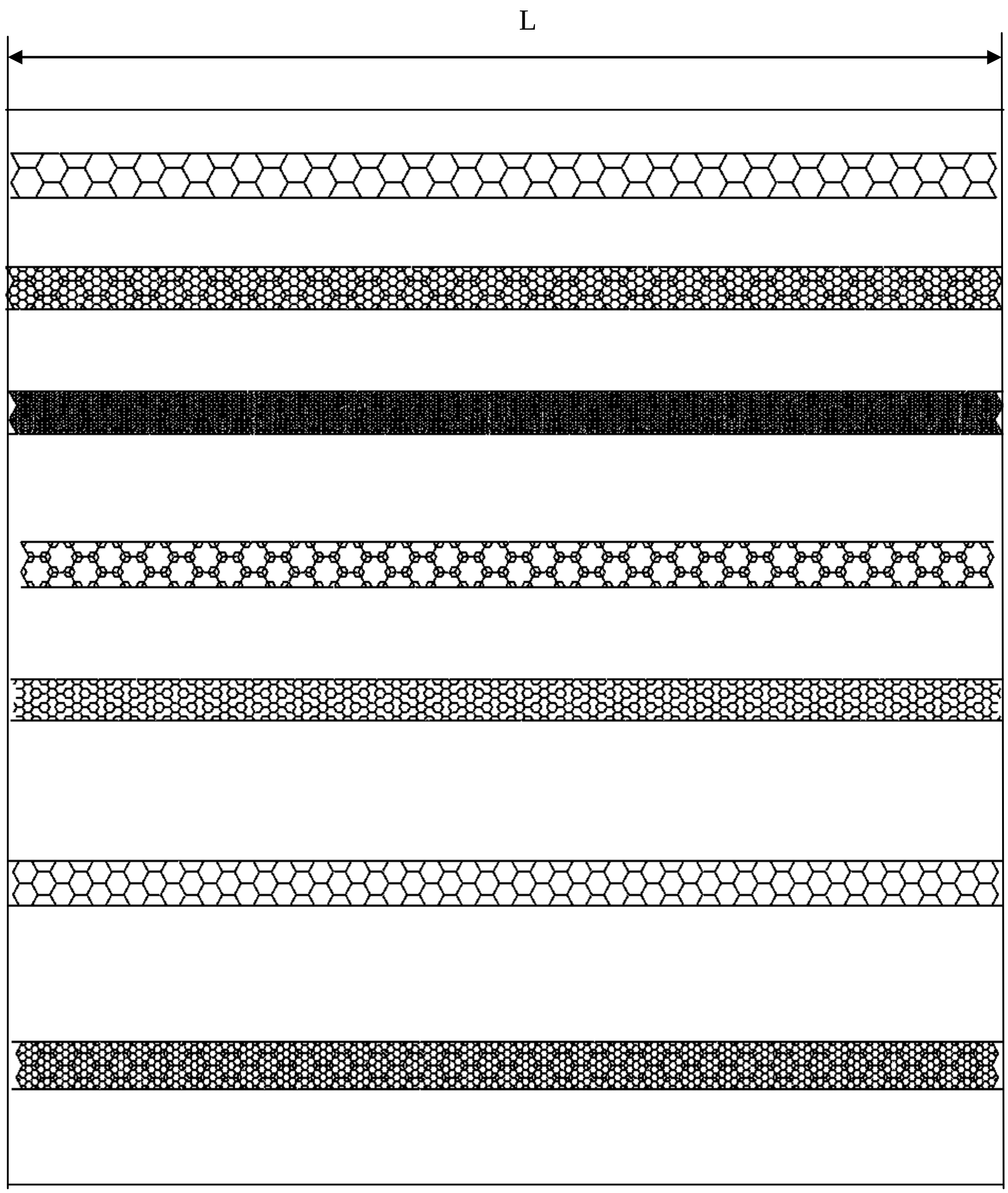


Figure 2.11: Zigzag configuration regular honeycomb core geometries used

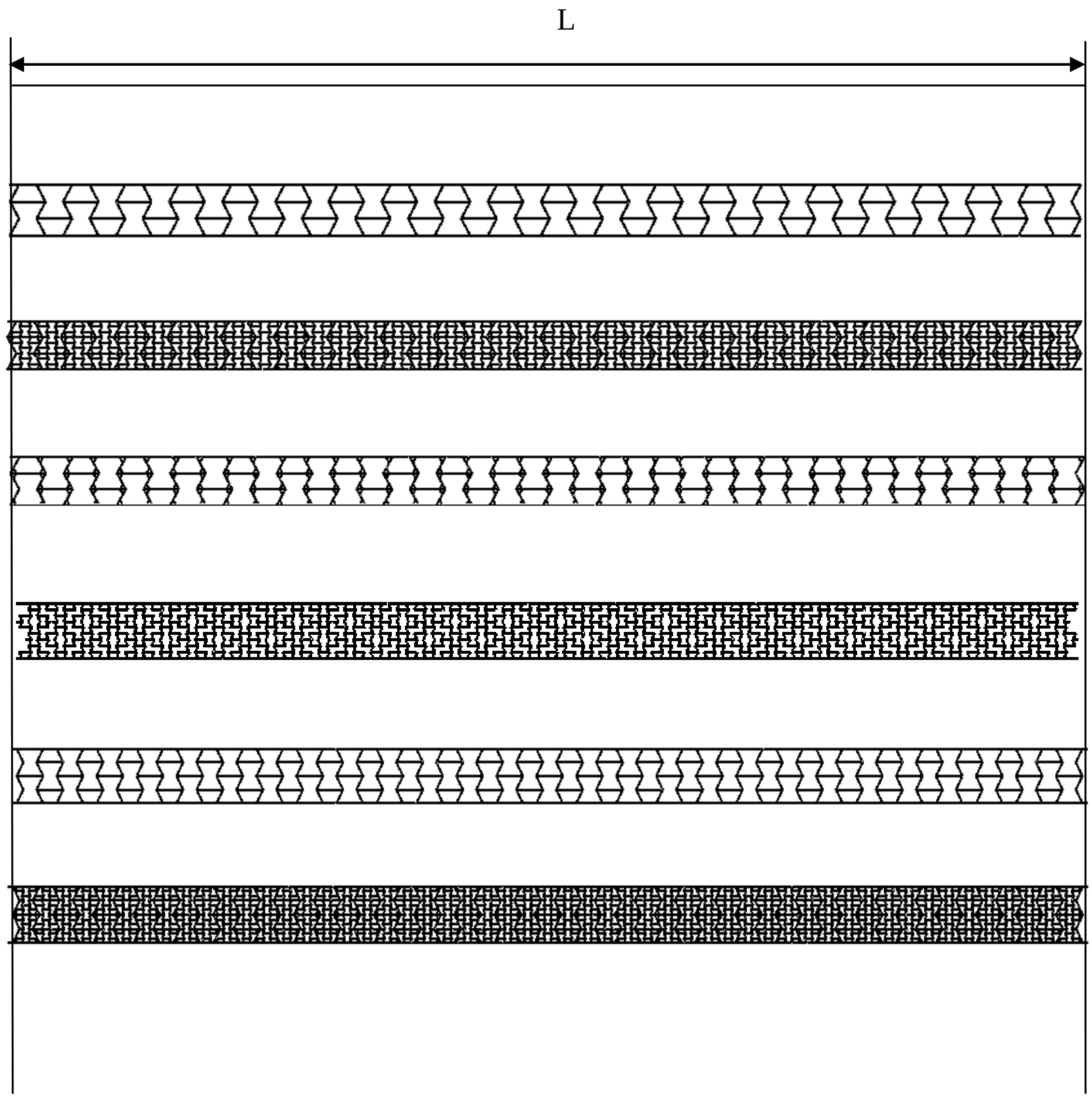


Figure 2.12: Zigzag configuration auxetic honeycomb core geometries used.

2.3 Model Setup for Armchair Configuration Honeycomb Structure

2.3.1 Construction of Level-0 Structures

The armchair configuration models are created by using a regular honeycomb unit cell with two stubs on either end of the vertex as shown in the Figure 2.13 a). The length of each stub is equal to half the length of the honeycomb, where length refers to the parameter l in Figure 2.2. This configuration has only one cell in the unit which is repeated to obtain the reference length of 2.016608m. For regular honeycomb with 30^{o} internal angle, $l = h$ .The length of the unit cell can be calculated as

$$Ly = 2(h + l\sin\theta) = H, \tag{2.8}$$

Therefore

$$l = H/(2*(1+\sin\theta)) \tag{2.9}$$

where H is the height of the core as shown in Figure 2.1, θ is 30^{o} for the regular honeycomb and –30^{o} for auxetic honeycombs and l is length of a level-0 honeycomb as shown in Figure 2.2

2.3.2 Construction of Level-1 Structures

The level-1 structure is created by placing seven smaller regular honeycombs inside the each level-0 honeycomb for the regular honeycomb model. For the auxetic model the level-1 honeycomb is created by placement of seven smaller auxetic honeycombs in same order as the regular honeycomb. The geometric relations used in the calculating the length of level-1 honeycombs is given below,

$$l_0 = 3l_1 \; . \tag{2.10}$$

Therefore

$$Lx = 6l_1 \cos\theta \qquad \textbf{(2.11)}$$

where Lx refers to the dimension in Figure 2.13, l_0 is the length of the level-0 honeycomb, l_1 is the length of level-1 honeycomb, θ is 30^o for the regular honeycomb and -30^o for auxetic honeycomb.

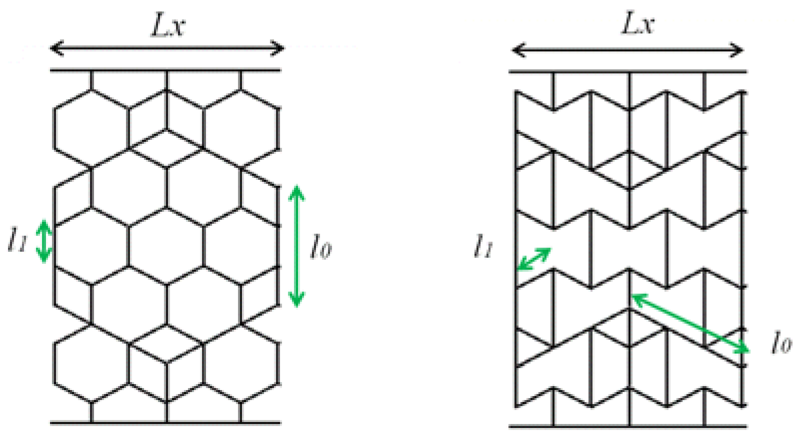


Figure 2.13 Construction of level-1 unit cell

2.3.3 Construction of Corner Reinforced and Level-1* Structures

The corner reinforced honeycomb is created by removing the level-1 honeycombs in the center of the level-0 honeycombs, except the corner honeycombs. For regular honeycombs hexagonal corner reinforcement is created by this process whereas rhombic corner reinforcement is created for auxetic structures. This can be clearly seen in Figure 2.14 c) and in Figure 2.15 c)

The Level-1* structure is created by removing the entire level-0 honeycomb from the level-1 model for regular honeycombs. This can be seen in Figure 2.14 d) and in

Figure 2.15 d). The structure in 2.15 d) is modified to make it a feasible structure. Initially removing all the level-0 linkages resulted in a structure without proper linkage in the case of auxetic level-1* structure. The vertical stub like extensions were not removed in the level-1* structure to make it a feasible structure.

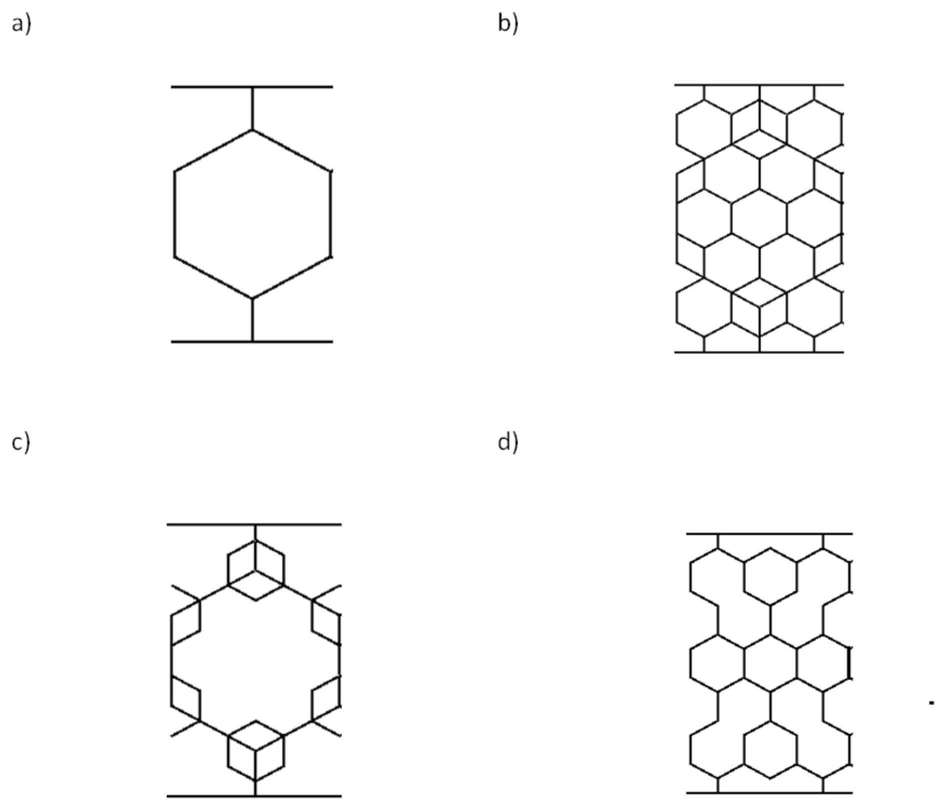


Figure 2.14: Armchair configuration regular honeycomb unit cells a) Level-0
b) Level-1
c) Corner reinforced
d) Level-1*

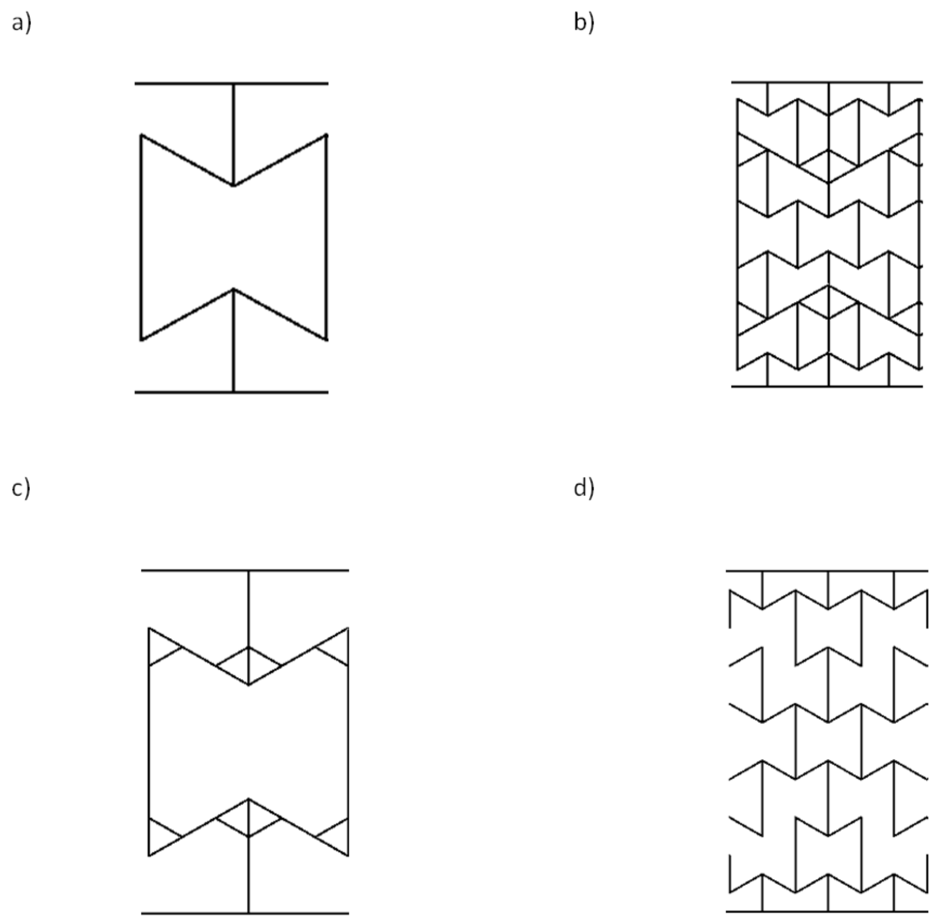


Figure 2.15: Armchair configuration auxetic unit cells a) Level-0

b) Level-1

c) Corner reinforced

d) Level-1*

2.3.4 Construction of Multilayered Structures

The multilayered armchair structures are created by adding another row of cells in the vertical direction of the sandwich panel. The geometric relation used for calculating the length of level-0 honeycomb is shown

$$l = H/(4*(1+\sin\theta)) \quad \textbf{(2.12)}$$

where H is the height of the core as shown in Figure 2.1, θ is 30^o for the regular honeycomb and -30^o for auxetic honeycombs and l is length of a level-0 honeycomb as shown in Figure 2.2. The level-1 cell length is calculated using the same geometric relations of single layered structure, but with the dimension of multilayered level-0 cells. The resulting multilayered structures is shown in Figure 2.16 and 2.17

2.3.5 Sandwich Panels of Various Core geometries

The Figure 2.18 and 2.19 gives a clear idea about the panels used in the study. As discussed earlier all panels have a constant length and constant mass. The single layered regular and auxetic panels of armchair configuration have 40 cells in the length direction. The multilayered regular and auxetic panels have 80 level-0 cells in the length direction.

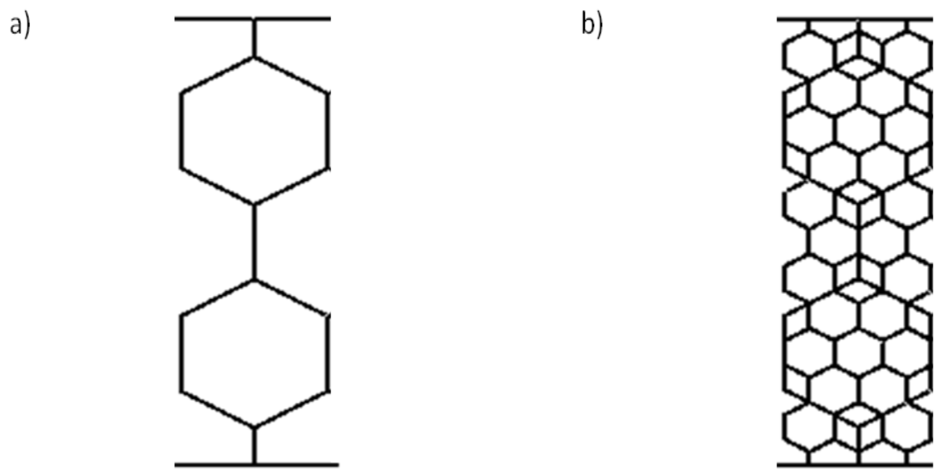


Figure 2.16: Armchair configuration multilayer regular honeycomb unit cells
a) Level-0 b) Level-1

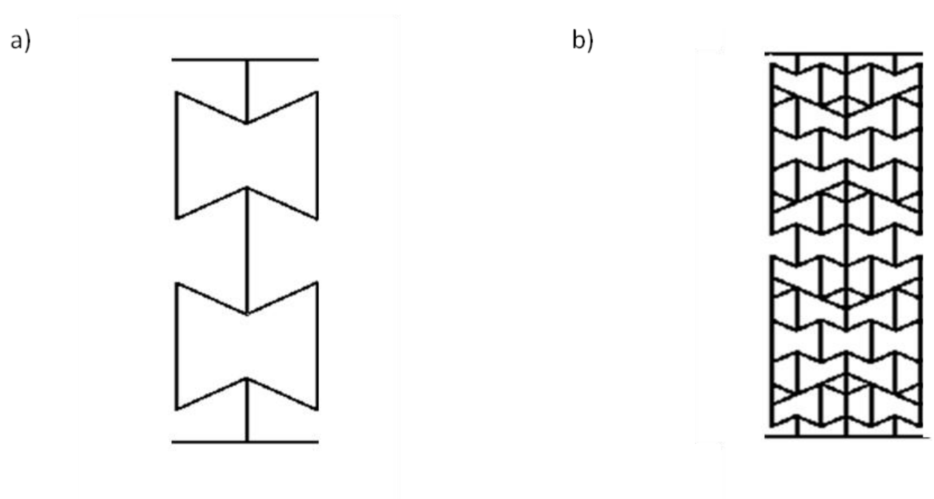


Figure 2.17: Armchair configuration auxetic multilayer unit cells
a) Level-0 auxetic honeycomb b) Level-1 auxetic honeycomb

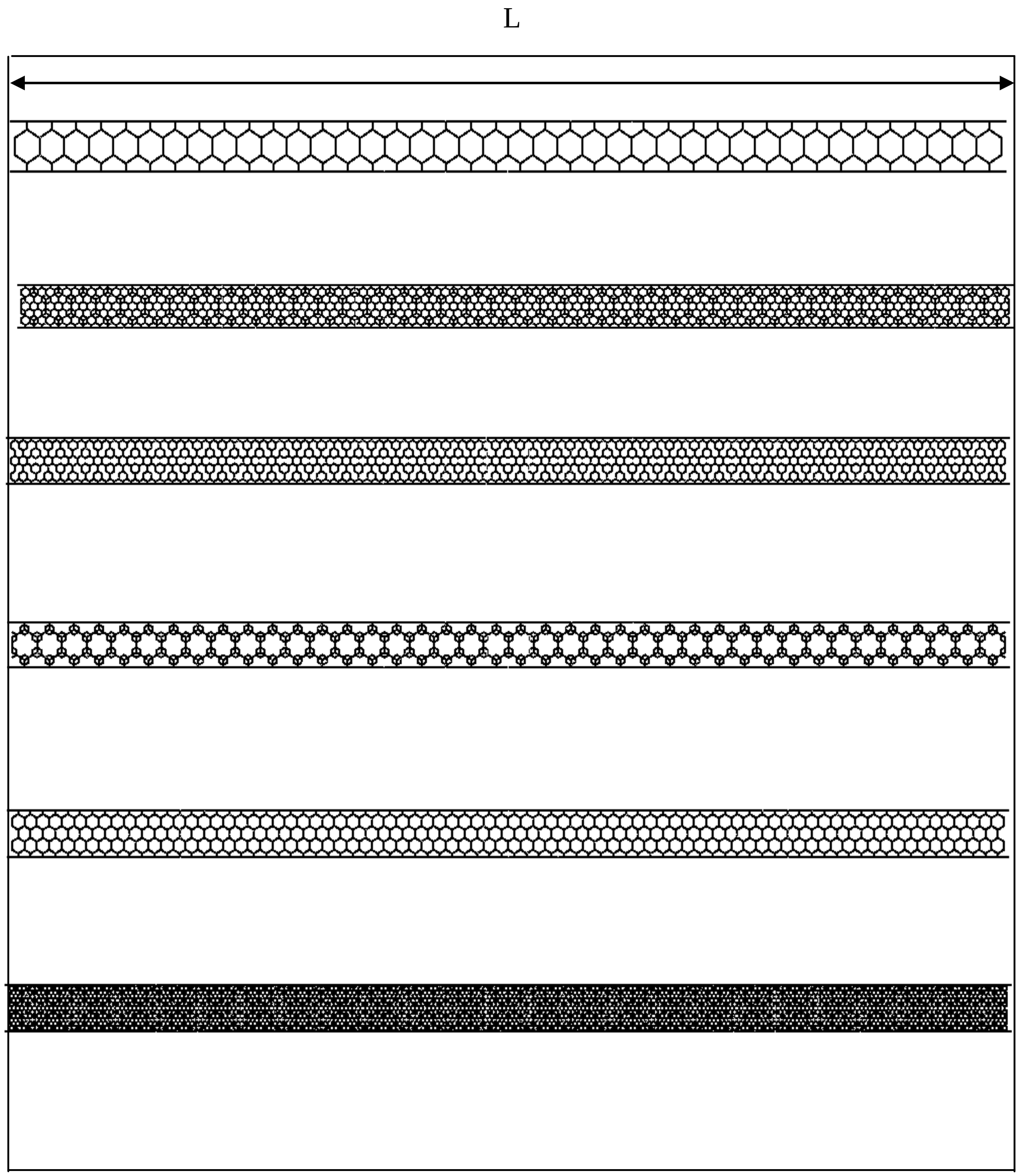


Figure 2.18: Armchair configuration regular honeycomb core geometries used in analysis

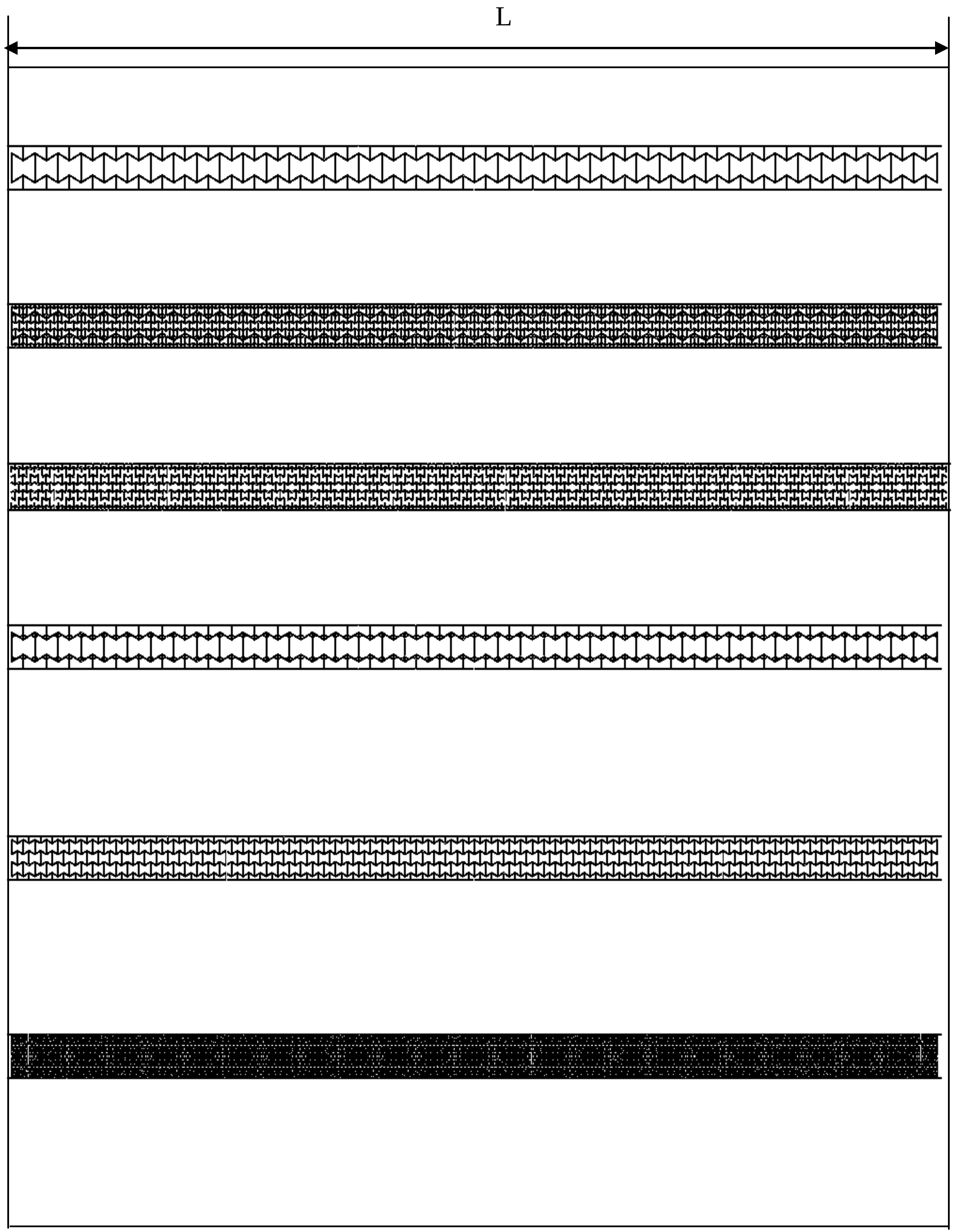


Figure 2.19: Armchair configuration auxetic honeycomb core geometries used in analysis

2.4 Thickness of Core

The thickness of the core is modified for each sandwich panel in order to maintain the mass constant. The reference mass is 73.96 kg, which is the mass of the sandwich panel made up of regular level-0 honeycombs of armchair configuration made with sandwich panels which are 2.0 meter long. This is a special case, as the thickness of the sandwich core and the face plates are equal. Mass is maintained constant for all the sandwich panels by changing the thickness of the core for each panel. The thickness can be calculated as

$$\frac{M}{p} = l_c \cdot t_c + t_f . l_f \qquad \textbf{(2.13)}$$

where M refers to the mass of the entire panel which is taken as 73.96 kg, i.e., reference mass, p is the density per unit depth, i.e., 2700 kg/m^3 which is the density of aluminium, l_c is the total length of the core, t_c is the thickness of the core, l_f is the total length of the faceplate, t_f is the thickness of the faceplate. The thickness of various levels of honeycomb used in effect of thickness ratio study can be calculated as

$$\frac{M}{p} = l_{c0} \cdot t_{c0} + l_{c1} . t_{c1} + t_f . l_f \qquad \textbf{(2.14)}$$

where M refers to the mass of the entire panel which is taken as 73.96 kg, p is the density per unit depth which is 2700 kg/m^3, l_{c0} is the total length of the core made up of level-0 cells, t_{c0} is the thickness of the core made up of level-0 cells, l_f is the total length

of the faceplate, t_f is the thickness of the faceplate, t_{c1} is the thickness of the core made up of level-1 cells, l_{c1} is the total length of honeycomb made up of level-1 cells.

The Table 2.1 presents the calculated thickness of the core for structures with uniform thickness and Table2.2 for structures with varying thickness within level-0 and level-1 honeycomb respectively.

Table 2.1: Cell wall thickness of constant mass panel with uniform thickness

	Zigzag Configuration		**Armchair Configuration**	
Model	**Regular (mm)**	**Auxetic (mm)**	**Regular (mm)**	**Auxetic (mm)**
Level-0	3.1860	2.5580	2.4880	1.8621
Level-1	0.8248	0.6576	0.6801	0.5341
Corner reinforced	1.2886	1.8350	1.0689	1.3988
Level-1*	1.1128	0.8467	0.9350	0.7022
Multilayered Level-0	2.3470	1.8515	1.2466	0.9340
Multilayered Level-1	0.6151	0.5074	0.3404	0.2674
Level-2	0.2570	-	-	-

Table 2.2: Cell wall thickness of constant mass panel with non-uniform thickness zigzag configuration structures

Model	Zigzag Configuration			
	REGULAR (MM)		AUXETIC (MM)	
	Level-0	Level-1	Level-0	Level-1
Ratio-1(L1/L0)	0.8247	0.8247	0.6576	0.6576
Ratio-0.5(L1/L0)	1.3103	0.6551	1.0463	0.5231
Ratio-2(L1/L0)	0.4737	0.9473	0.3773	0.7546

Table 2.3: Cell wall thickness of constant mass panel with non-uniform thickness armchair configuration structures

Model	Armchair Configuration			
	REGULAR (MM)		AUXETIC (MM)	
	Level-0	Level-1	Level-0	Level-1
Ratio-1(L1/L0)	0.6801	0.6801	0.5341	0.5341
Ratio-0.5(L1/L0)	1.0685	0.5343	0.8313	0.4157
Ratio-2(L1/L0)	0.3938	0.7877	0.3115	0.6229

2.5 Properties of Honeycomb Sandwich Panel

2.5.1 Effective Properties of Honeycomb Core

Gibson and Ashby in their book [16] had studied the mechanical properties of honeycombs for both in-plane and out of plane properties. A hexagon having regular side, all angles 120^o and with same cell wall thickness will have an isotropic in plane properties. Such a model will have two independent elastic moduli namely the Young's modulus and Shear modulus. But an irregular hexagon or a hexagon with different wall thickness in different direction will have anisotropic properties. This honeycomb has four moduli. Based on geometrical relations they found the relative density, which is one of four moduli, to be

$$\rho^* = \rho \frac{\left(\frac{t}{l}\left(\frac{h}{l}+2\right)\right)}{2\cos\theta\left(\frac{h}{l}+\sin\theta\right)} \tag{2.6}$$

and when $\theta = 30^o$ and $h=l$, the relative density reduces to

$$\rho^* = \rho \frac{2}{\sqrt{3}}\frac{t}{l}. \tag{2.7}$$

The relative density is another important parameter which is used to maintain the mass constant in our work. They conducted linear elastic deformation studies by loading the regular honeycomb in the X1 or X2 direction i.e. unidirectional loading. The results were found to be same for both tensile and compressive loading. The shear modulus and the Young's modulus parallel to X1 and X2 direction are

$$G_{12}^{*}=E\left(\frac{t}{l}\right)^{3}\frac{\left(\frac{h}{l}+\sin\theta\right)}{\cos^{3}\theta} \quad \textbf{(2.8)}$$

$$E_{11}^{*}=E\left(\frac{t}{l}\right)^{3}\frac{\cos\theta}{\left(\frac{h}{l}+\sin\theta\right)\sin^{2}\theta} \quad \textbf{(2.9)}$$

$$E_{22}^{*}=E\left(\frac{t}{l}\right)^{3}\frac{\left(\frac{h}{l}+\sin\theta\right)}{\left(\cos^{3}\theta\right)} \quad \textbf{(2.10)}$$

where h, l, θ *and* t are the geometric parameters referred to in Figure 2.2. E and ρ are the Young's modulus and density of the material, which is Aluminum in our case.

2.5.2 Effective properties of sandwich panel

The effective properties of sandwich panels are discussed in this section. Though we are interested in the properties of core geometry, the face sheet is an important contributor for the properties of the entire panel.

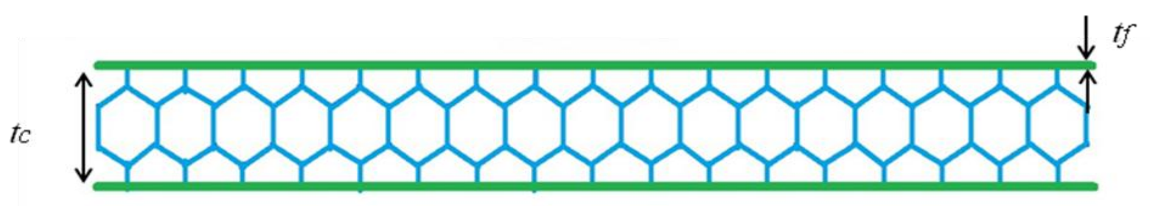


Figure 2.20: Core thickness

The bending stiffness of honeycomb panel is defined as

$$D_1 = \frac{1}{3}\left\{ \frac{2E_f}{1-(v_f)^2}\left[\frac{3}{2}t_c\, t_f^2 \ + \frac{3}{4}\ t_c^2 t_f \ + t_f^3\right] + \frac{E_{11}^*}{1-(v_c)^2}\frac{t_c^3}{4}\right\} \qquad \textbf{(2.11)}$$

where E_f is the Young's Modulus of the face sheet which in our case is made up of aluminium, t_c and t_f are the height of the core and the thickness of face sheet respectively as shown in Figure2.20, v_f is the Poisson's ratio of the face sheet which is equal to 0.3 in our case and v_c is the effective Poisson's ratio obtained from

$$v_c^* = \left[\frac{\cos^2\theta}{(\alpha+\sin\theta)\sin\theta}\right]\left[\frac{1+(1.4+1.5v)\beta^2}{1+\left(2.4+1.5v+\cot^2\theta\right)\beta^2}\right] \quad , \qquad \textbf{(2.12)}$$

where $\alpha = \frac{h}{l}$ and $\beta = \frac{t}{l}$.

The plane shear stiffness for the honeycomb sandwich plate is also given below

$$D_{66} = \frac{1}{3}\left\{2G_f\left[\frac{3}{2}t_c\, t_f^2 + \frac{3}{4}t_c^2\, t_f \ + t_f^3\right] + G_{12}\ \frac{t_c^3}{4}\right\} \qquad \textbf{(2.13)}$$

Where G_f is the shear modulus of the material and in our case it is aluminum.

2.5.3 Comparison of Bending Stiffness of Sandwich Panel

Table 2.4 compares the static bending stiffness of sandwich panels made up of level-0 auxetic and regular honeycomb cores. The values of Table 2.4 are computed using the thickness values from Table 2.1

Table 2.4: Bending stiffness of honeycomb sandwich structures with faceplate thickness .0025m

Configuration	Layers	Model	Bending Stiffness(Nm)
Armchair	Single	Regular	790460
	Single	Auxetic	785760
	Multiple	Regular	790490
	Multiple	Auxetic	785770
Zigzag	Single	Regular	792710
	Single	Auxetic	786770
	Multiple	Regular	792270
	Multiple	Auxetic	786520

From the Table 2.4 we observe that the bending stiffness of zigzag orientation structures is stiffer than the armchair orientation structures on an average by 0.18%. Among each configuration the regular structures are stiffer than auxetic structures irrespective of the number of layers. The single layer structures have higher stiffness when compared with their respective multi layered regular structures with the exception of multilayered auxetic armchair structure.

In order to find the contribution of the face plate to the stiffness of the panel a separate study was conducted with reduced thickness of face plate. The thickness was reduced from .0025m to .001m. The bending stiffness values of various structures are presented in Table2.5.

Table 2.5: Comparison of bending stiffness of honeycomb sandwich structures with faceplate thickness .001m and .0025m

Configuration	Layer	Model	Bending Stiffness With Thickness Of Face Sheet=.0025m (Nm)	Bending Stiffness With Thickness Of Face Sheet=.001m (Nm)	% Decrease
Armchair	Single	Regular	790460	318400	59.72
	Single	Auxetic	785760	306820	60.95
	Multiple	Regular	790490	318420	59.72
	Multiple	Auxetic	785770	306850	60.95
Zigzag	Single	Regular	792710	323950	59.13
	Single	Auxetic	786770	309310	60.69
	Multiple	Regular	792270	322900	59.24
	Multiple	Auxetic	786520	308690	60.75

From Table2.5 we can observe that reducing the thickness of faceplate by 60 % has created 59.95 % decrease in the average static stiffness of zigzag structures and 60.33 % decrease in the average static stiffness of armchair structures. An important observation was that when the thickness of face plate was reduced, the thickness of the core had to be increased in order to maintain the mass constant.

CHAPTER-3

STRUCTURAL- ACOUSTIC MODEL OF SANDWICH PANEL

This chapter deals with setting up of the acoustic model for extraction of natural frequency and calculation of sound pressure levels of the sandwich panels. The model consists of an air domain, which is coupled to the top face plate of the sandwich panel as shown in Figure 3.1.The sandwich panel is pinned to rigid baffles on either side. The size of the air domain is created based on convergence studies. The boundary of the air domain has to be far enough not to reflect any sound back into the system. This model is replicated from previous studies [32] on acoustical properties of honeycomb sandwich panels. This model has been used in several other studies [40]. During the previous studies the validity of the model has been cross checked with results from custom made matlab codes and also experimental results [40, 32]. A 2 D model is used for the study as it reduces the processing time significantly and also the geometry creation time. Another important reason is that the loading is in the same plane of the geometry. An important assumption is made in this 2D analysis; since the out of plane thickness is large enough the corresponding boundary effects are neglected. The aspect ratio which is ratio between the length of the shortest beam and the thickness of the beam was checked for all the structures and was found to vary between 5-18 .The aspect ratios are given in APENDIX E.

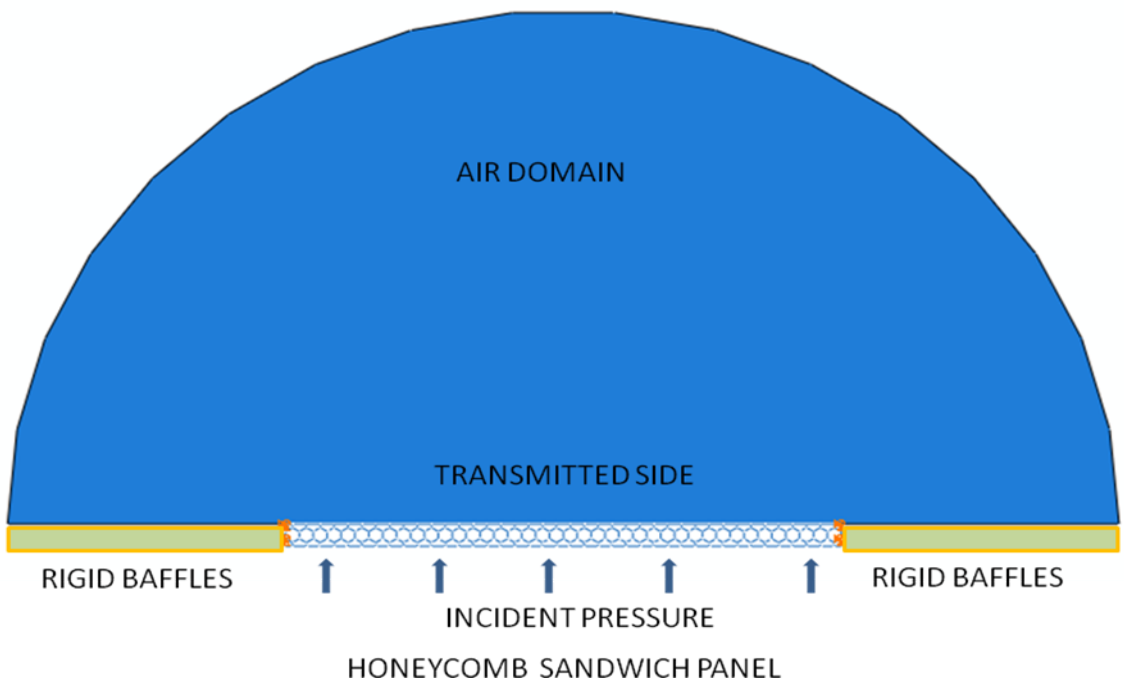


Figure 3.1: Setup for structural acoustic model showing finite panel supported at ends embedded in rigid baffle.

3.1 Parts and Material Properties

The model consists of two parts namely the air domain and the honeycomb sandwich panel. The honeycomb sandwich panel is modeled as a single 2D planar deformable part with wire profile. The various core geometries discussed in chapter 2 are created as part for the analysis. For natural frequency extraction only the honeycomb sandwich panel is used without the air domain. Two different rectangular sections are created separately, one of the face sheet and another for the honeycomb core. In hierarchical core panels, additional sections are created for effect of ratio of thickness studies. Next the profiles are created for the face sheet and cores separately. The parameter ‘b’ refers to the x-y thickness of the profile. This is the parameter which is

modified to maintain the mass constant. The parameter ‘a’ refers to the out of plane thickness and is maintained as 1m for all the analysis. Finally all the section as assigned the material properties of aluminium. The density is 2700 kg/m^3, Poisson’s ratio is 0.3 and Young’s modulus of 71.9 GPa. This material property is maintained constant for all the models.

The air domain is semicircular in shape with a radius of 2 meters. This is used to simulate the effect of air surrounding the sandwich plate on the transmitted side. The air provides resistance to the velocity of the particles in the sandwich plate. It is also used to obtain the sound pressure level of the sound transmitted to the air domain. The domain is modeled as 2D deformable part. The model is assigned a solid homogeneous section with the material properties of air. The density of air ρ= 1.2 kg/m ^{3}, bulk modulus K= 141179 Pa and the speed of sound is air c= 343.996 m/s. The out of plane thickness is made 1 m.

3.2 Mesh Type and Mesh Seed

The face sheet and the honeycomb core are meshed using B22 element. The B22 element is a three node quadratic beam element. This element is chosen as it is a perfect tradeoff between accuracy and high computational load. Also the seed size is chosen such that there are four elements in the smallest edge of honeycomb core as done in previous work. [40, 32] And so there is no common seed size, each model has its own seed size, since the smallest edge in each geometry is different.

The air domain is meshed using AC2D4. These are 4-node bilinear acoustic elements. Since a quadratic mesh is more accurate than a triangular mesh AC2D4 is used instead of AC2D3. Also the entire domain is meshed uniformly with a seed size of 0.012

m. As per the Abaqus user manual recommendations there should be at least 6-8 elements per wavelength of the highest analyzed frequency for acoustic radiation analysis [47]. The wavelength of the highest analyzed frequency for the current analysis can be calculated as

$$\lambda = c / 2\pi f = 0.0547 \text{ m} \qquad \textbf{(3.1)}$$

where c is the speed of sound in air, f is the frequency in Hz.

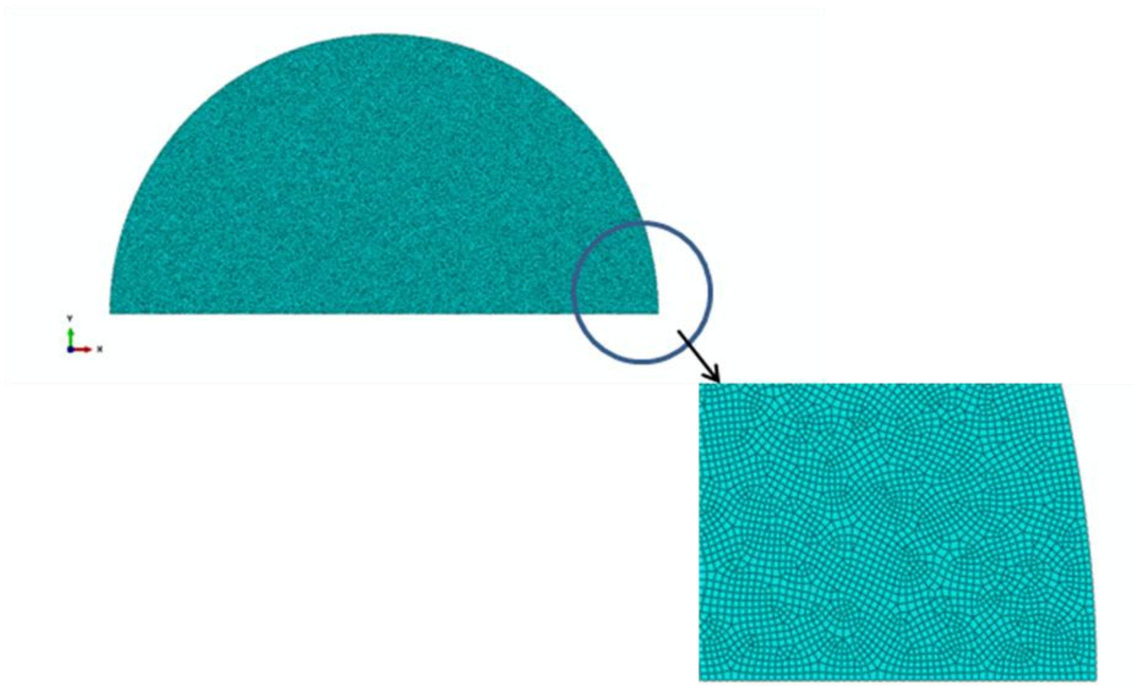


Figure 3.2: Mesh of air domain with rectangular elements

3.3 Constraints

The tie constraint is used to tie the honeycomb top surface to the bottom surface of the air domain. The top surface of the face sheet is the master surface while the bottom surface of the air domain is the slave surface. The tie constraint ensures that there is no relative motion between the two surfaces as it makes the rotational and translational motion and also the active degrees of freedom equal for the pair of surface i.e. master and slave surface.

To prevent the sound waves from getting reflected back from the boundary, non reflecting boundary conditions are used on the outer surface of the air domain. An acoustic impedance of type non- reflecting is created with circular profile on the outer boundary of the fluid domain. This helps to simulate an effect of open area of infinite volume of air surrounding the honeycomb. The geometry is specified as circular with 2 m radius. An alternative to the non reflecting boundary condition method is the infinite elements method which is more accurate than the former method.

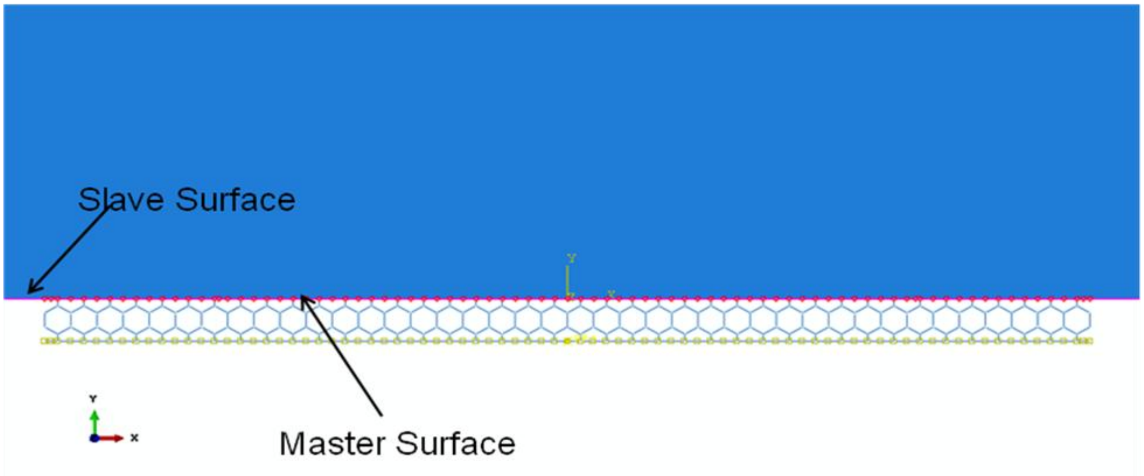


Figure 3.3: Tie constraint

3.4 Loads and Boundary Condition

The honeycomb structure is loaded with a uniformly distributed pressure load on the lower side of the bottom face sheet of the honeycomb panel. This pressure load mimics the effect of sound wave on the input side. This is a unit pressure load which varies sinusoidally. In this work, the incident angle for the sound waves is set to zero for the experiments. There have been previous studies which studied the effect of varying angle of incidence, so we are maintaining a constant value throughout all simulations. And this unit pressure load is not applied during the natural frequency extraction procedure.

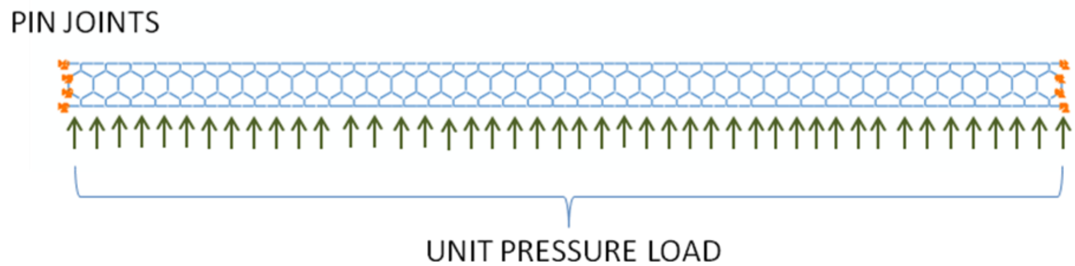
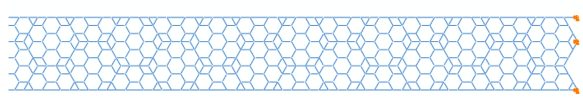
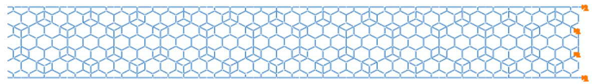


Figure 3.4: Loads and boundary conditions

The sandwich panel is held in the model using pin joints as shown in the Figure. Pin joints restrict the motion in x and y direction, while the rotation in the out of plane direction is not constrained. The boundary condition is applied to the nodes on the left and right edge of the panel and on the honeycomb it is applied to the vertex of the honeycomb. This boundary condition and load is consistent throughout the study for both natural frequency extraction and for the steady state direct analysis for structures belonging to the same configuration. For zigzag configuration there are three nodes on each side of the panel and for armchair configuration there are four nodes on each side of the panel which are constrained as shown in Figure3.5 The joints are either attached to the vertex of the level-0 honeycomb structures or on vertex on the level-1 structure which is closest to the level-1 vertex in the case of level-1* structures.



a)



b)

Figure 3.5 Boundary conditions a) Zigzag orientation structures b) Armchair orientation structures

3.5 Natural Frequency Extraction

The natural frequency extraction is an important procedure for finding the natural frequency of the sandwich panel. This data is later used in the steady state analysis for sweeping across various frequency ranges. It is to be noted that the model used for the extraction procedure is un-damped. The analysis is run using a Lanczos Eigen solver over the frequency range of 1~1000 Hz as this is the area of the interest for this work i.e. the stiffness and the resonance region. The frequency extraction procedure is given in the Abaqus theory manual. [47] It is a linear perturbation procedure and works by finding the Eigen values to calculate the natural frequency and corresponding mode shapes of the system. Though the Lanczos Eigen solver is capable of finding natural frequency for coupled structural acoustic problems we are using only the panel for natural frequency extraction, as it is less time consuming. The two steps used in the procedure are

1. Initial – This is the default step which is predefined in Abaqus. This is not modified.

2. Linear perturbation, frequency step- This is the step where the Lanczos solver is chosen. The maximum frequency for the analysis is given as 1000 Hz.

3.6 Steady State Dynamic Analysis

The method used in this analysis is the mode based steady state dynamic analysis and response of this analysis is based on modal superposition technique. This is a linear perturbation procedure which calculates the steady state dynamic linearized response of a system to harmonic excitation. This method requires the natural frequency to be extracted beforehand. The system is damped with a structural damping of 0.01 before running the analysis. In this analysis both the air domain and honeycomb panel are used. The two steps involved in this analysis are given below.

1. Initial – This is the default step which is predefined by abaqus automatically .This is not modified.

2. Steady state dynamics, direct- This step is created by selecting the linear perturbation procedure type and then steady state dynamic direct. The Eigen values which were extracted earlier are used to create the frequency range. Each frequency range is subdivided into 7 bands of frequency spacing. The bias is given as 2. A bias of 1 makes the frequency spacing equal while a bias of 5 will shift the frequency points towards the end of the range. The effect of bias is shown below in the Figure 3.5.

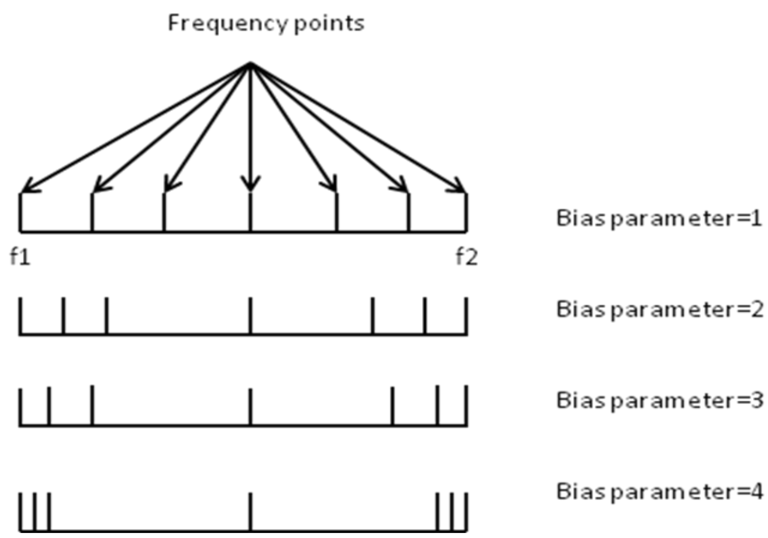


Figure 3.6: Effect of bias on the frequency range

3.7 Sound Pressure Level Extraction

Once the setup is ready for analysis, a set containing the nodes on the top surface of the honeycomb sandwich panel is created. A history output for the acoustic pressure values i.e. POR values is requested for the set created. It should be noted that the values of POR obtained are complex numbers, so while extracting the values the magnitude of the POR should be obtained. The history output is a more useful tool compared to the field output request. It stores data at specific points in the model.

The sound pressure level is calculated and plotted using a matlab code which uses the acoustic pressure data obtained from the history output from Abaqus. The formula for calculating sound pressure level is

$$SPL = 20\log_{10}\left(p / p_{ref} \right)$$

where p refers to the acoustic pressure in Pascal which is calculated in Abaqus, while p_{ref} is the standard reference pressure which is $20\mu Pa$ for air. The incident sound of 1 Pa corresponds to Sound pressure level of 94 dB.

3.8 Model Accuracy

The setup used in the study has been used in many past works [32, 40]. But in order to verify the accuracy of the analysis results, mesh convergence studies were conducted for air domain and sandwich panel separately. To check the accuracy of the mesh for the sandwich panels a mesh with four different seed size are compared. Each of these seed size is chosen so that there are one, two, three and four elements in the smallest link of the honeycomb, as shown in Table 3.1. The results of this comparison are given in Figure 3.7. There is not much difference in the sound pressure level between a fine and course mesh, expect once the frequency increases the coarse mesh shifts the frequency to the left. For each of this model the seed size used for the air domain is kept 12 mm. The meshes used for the seed sizes used in Table3.1 are shown in Figure3.8

Table 3.1: Seed size used for panel mesh convergence study

Mesh Seed Size(m)	**Number of Elements Per Shortest Edge of the Honeycomb**
0.01	1
0.005	2
0.0025	4
0.0020	5

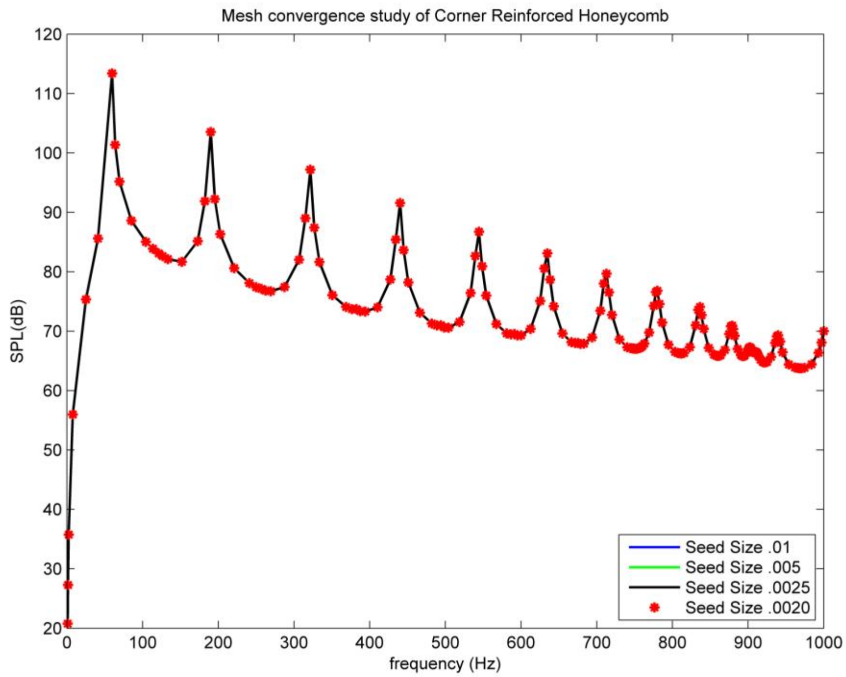


Figure 3.7: Mesh convergence study for panel

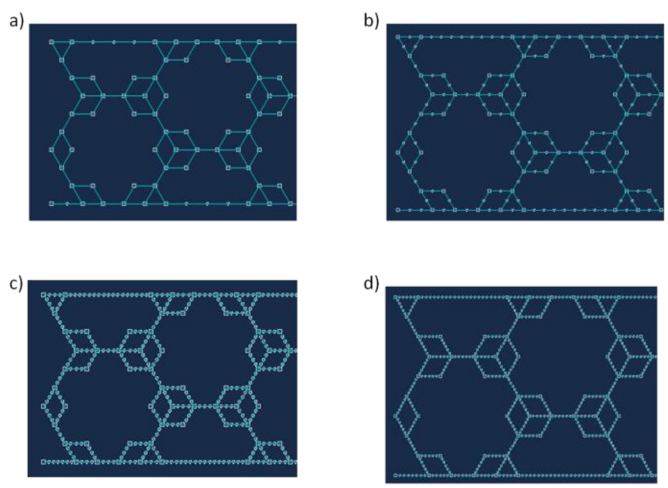


Figure 3.8: Various seed size a) Seed size-.01 b) Seed size-.005 c) Seed size-.0025 d) Seed size-.002

For the air domain the mesh convergence is studied using four different meshes. A coarse mesh of seed size 80mm for the air domain is compared with a fine mesh of 12mm to 80mm, 12mm and 8mm. The next plot shown in Figure 3.9 compares the various transmitted sound pressure levels for different seed sizes used for the air domain while the seed size for the honeycombs is kept constant at 0.0025m. We can see that the result converges for a mesh size of 12mm. The finer mesh with seed size of 8mm did not create any drastic change in results, though there was change in the sound pressure transmitted at higher frequency. These changes can be seen in Figure 3.10

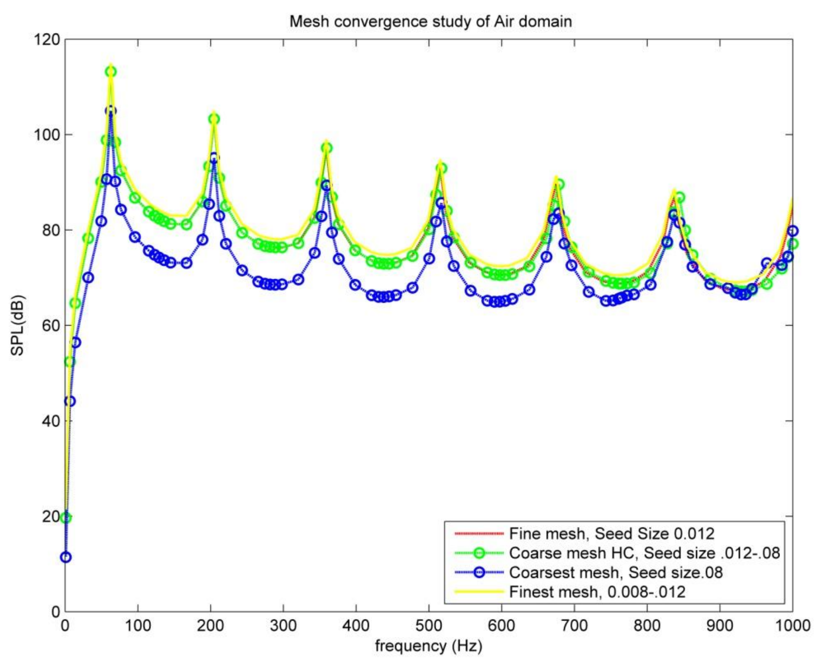


Figure 3.9: Mesh convergence study for air domain

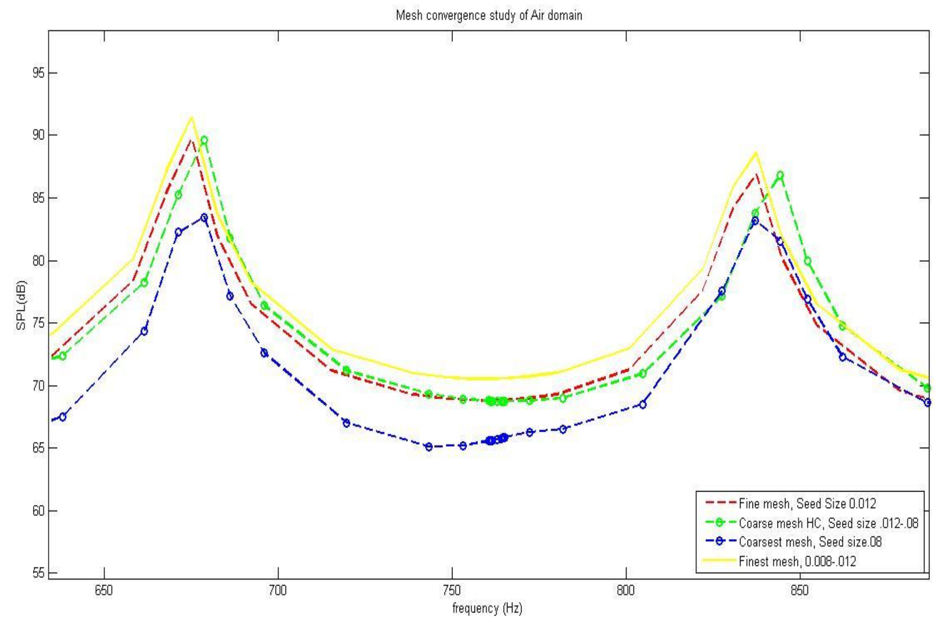


Figure 3.10: Mesh convergence study for air domain zoomed in view

CHAPTER – 4

RESULTS OF NATURAL FREQUENCY EXTRACTION

The natural frequency is extracted for all the structures before proceeding with the steady state dynamic analysis. In this chapter we will discuss the results of the natural frequency extraction procedure for the all the structures. Also the flexural and dilatory mode shape and their occurrence are discussed. The frequency at which pure standing wave fields can occur in a given system in free vibration are known as characteristic or natural frequency of the system. The associated spatial distribution of vibration amplitudes are known as the characteristic function or natural modes of the system [45]. The natural frequency of structure is the frequency at which the structure will vibrate without any external force acting on it. Resonance occurs when the external excitation frequency matches the natural frequency of the structure. Hence it is important to find the natural frequencies of a structure. Resonance is an important phenomenon as it may lead to large amplitude response to excitation and can lead to structural failure.

4.1 Natural Frequency of Zigzag Configuration Structures

The natural frequency of a structure depends on the mass and the stiffness of the panel. Since we have maintained the mass constant it implies higher the natural frequency higher the stiffness at a particular mode and vice versa.

4.1.1 Regular Honeycomb Structures

A list of the first 10 natural frequencies corresponding to panel bending for the regular honeycomb structures of zigzag configuration with single layer are presented in the Table 4.1. We observe the natural frequencies of level-1 and level-2 hierarchy match closely; with level-2 slightly lower. Both level-1 and level-2 vary considerably compared to level-0. The addition of hierarchy in level-1 and level-2 reduces the stiffness compared to level-0. Also, level-0 and level-1* natural frequencies match closely, showing that by removing the level-0 structure from level-1 hierarchy the resulting level-1* has nearly the same stiffness as level-0.

Table 4.1: First 10 natural frequencies of single layered regular honeycomb structures of zigzag configuration

Mode #	Level-0	Level-1	Level-2	Hexagonal corner reinforced	Level-1 *
1	61.703	52.137	50.942	59.751	59.457
2	126.26	105.41	102.82	121.28	120.88
3	199.13	165.07	160.84	190	190.71
4	271.68	224.45	218.59	257.07	260.76
5	343.29	283.88	276.43	321.61	330.64
6	413.18	343.02	334.08	382.67	399.7
7	481.44	402.17	391.82	440.23	468.16
8	547.87	461.31	449.65	494.11	535.91
9	612.48	520.57	507.72	544.42	603.04
10	675.19	579.96	566.04	591.25	669.49

The plot shown in Figure 4.1 shows the natural frequencies up to 1000 Hz of all the single layered regular zigzag honeycomb structures. From this plot we see that the stiffness of the hexagonal corner reinforced structure matches the level-0 closely for the first few modes up to around 350 Hz, but changes drastically at higher frequencies. Also we can observe that all the structures have a shift in the rate of change of natural frequency around 750 Hz.

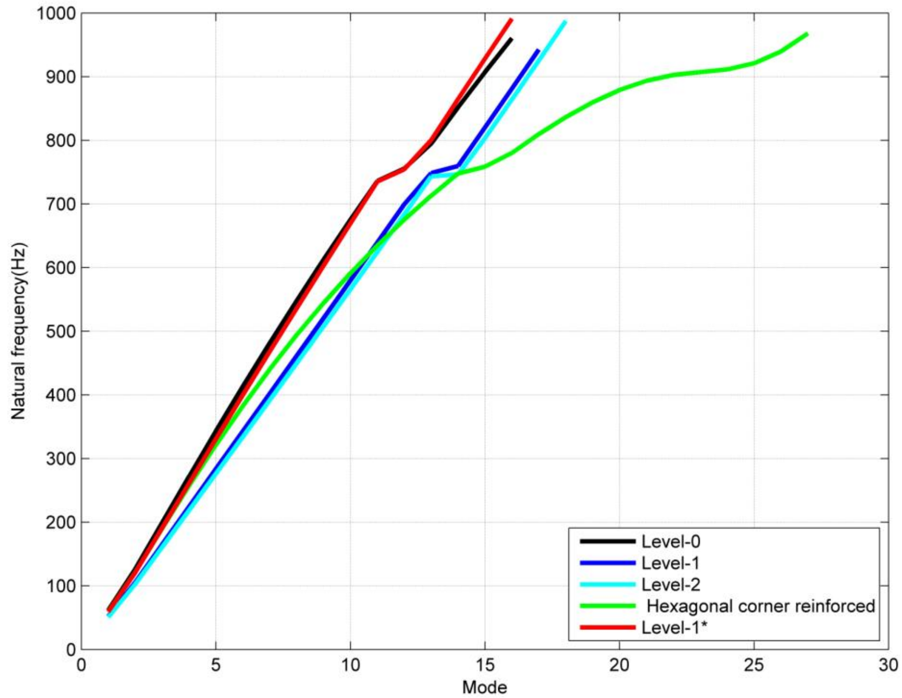


Figure 4.1: Natural frequency plot of zigzag configuration single layered regular honeycomb

Table 4.2 presents the values of single and multi layered level-0 and level-1 structures. Again all the structures have a shift in the rate of change of natural frequency around the 750 Hz in Figure 4.2. For level-0, moving from a single layer to multi layer shows a small change in natural frequency after the first 5 modes around 360 Hz. For level-1, the frequencies between a single and multi-layer were matching closely. In the case of level-1 hierarchy, this indicates that adding more level-0 layers will not change the frequencies significantly, due to the already relative large number of level-1 substructures.

Table 4.2: Comparison of first 10 natural frequencies of single and multilayered regular honeycomb structures of zigzag configuration

Mode #	Level-0	Level-1	Multi layer L-0	Multi layer L-1
1	62.62	48.896	63.14	51.343
2	129.77	98.617	130.06	104
3	205.99	153.96	205.7	162.65
4	283.13	208.99	281.41	220.96
5	360.96	264.16	356.54	279.31
6	439.09	319.23	430.38	337.43
7	517.83	374.49	503.07	395.58
8	597.14	429.94	574.46	453.78
9	677.14	485.74	644.56	512.14
10	757.8	541.92	713.27	570.7

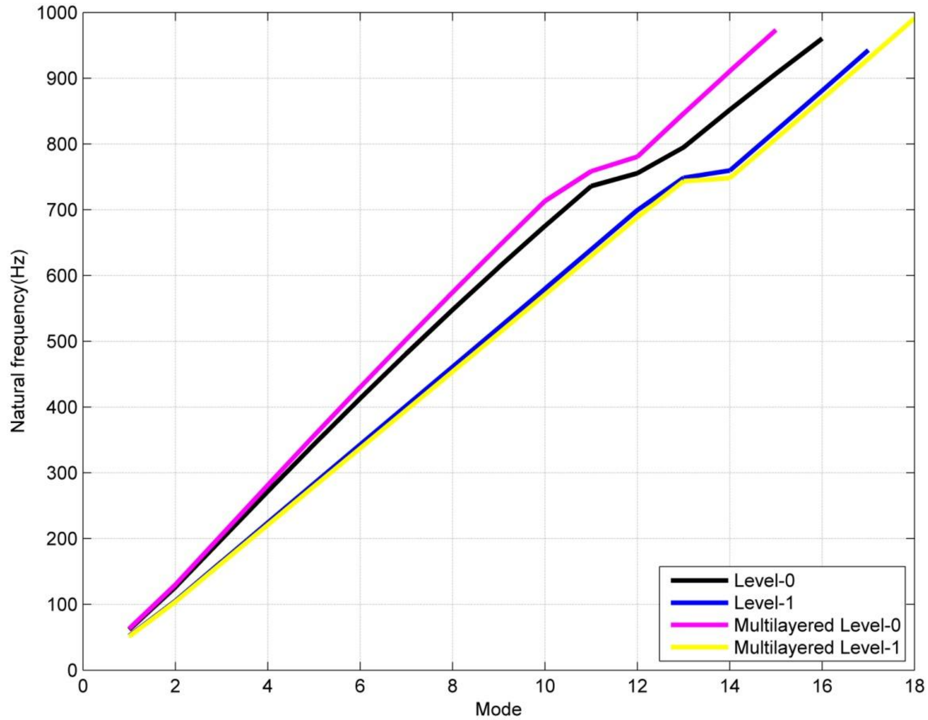


Figure 4.2: Comparison of natural frequency plot of zigzag configuration single layer and multilayered regular honeycomb structures

4.1.2 Auxetic Honeycomb Structures

Table 4.3 presents the first 10 natural frequencies of zigzag configuration single layered auxetic honeycomb structures. These modes are all flexural in nature.

Table 4.3: First 10 Natural frequency of auxetic honeycomb structures of single layered zigzag configuration

Mode #	Level-0	Level-1	Rhombic corner reinforced	Level-1*
1	27.593	25.343	30.882	18.91
2	55.178	50.854	61.716	37.797
3	84.171	77.883	94.404	57.537
4	112.98	105.35	126.75	77.494
5	141.95	133.71	159.13	97.932
6	171.05	163.08	191.48	118.92
7	200.37	193.68	223.89	140.6
8	229.94	225.63	256.38	163.05
9	259.81	259.05	288.97	186.37
10	290.01	294	321.69	210.63

From Figure 4.3, we observe that the only model which changes the rate of change of natural frequency around 750 Hz is the level-0 honeycomb. The level-1 structure has an increased stiffness beyond the 700 Hz range when compared to the level-0 structure.

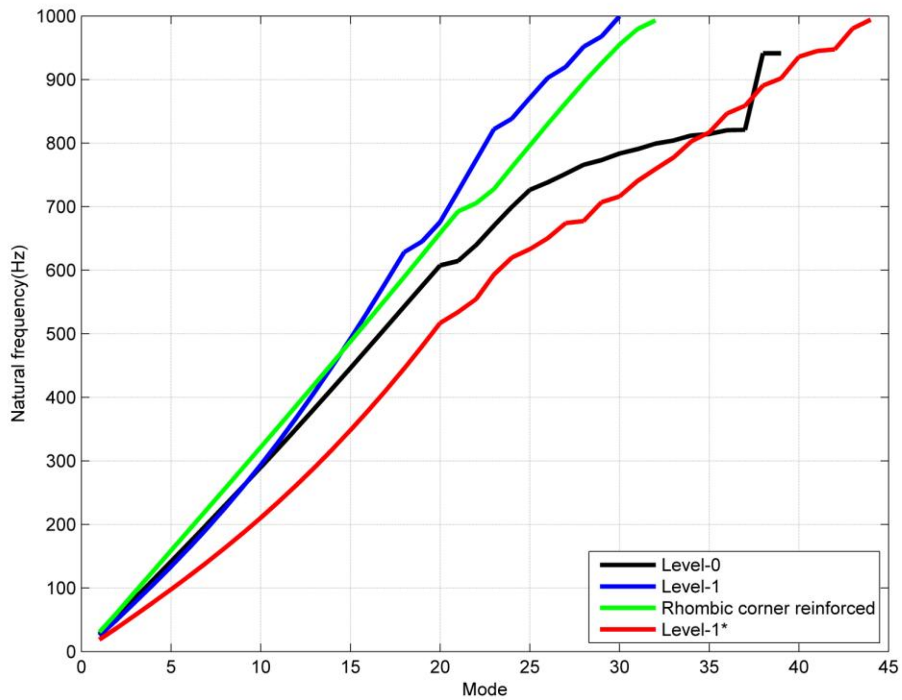


Figure 4.3: Natural frequency plot of zigzag configuration single layered auxetic honeycomb structures

Also the corner reinforced structure has similar natural frequencies when compared to the level-1 structure up to 700 Hz, beyond which the natural frequency of corner reinforced structures decreases. The level-1* structure maintain a constant rate of change of natural frequency throughout the frequency range and less stiff than the level-0 structure throughout the frequency range except for mode 35-38.

A special case of the level-1* called the modified level-1* is shown in Figure 4.4 was studied. The structure is a created by removing three links from level-1* marked in red as shown in Figure 4.4. The removal of links isolates the level-1 structures of two consecutive unit cells.

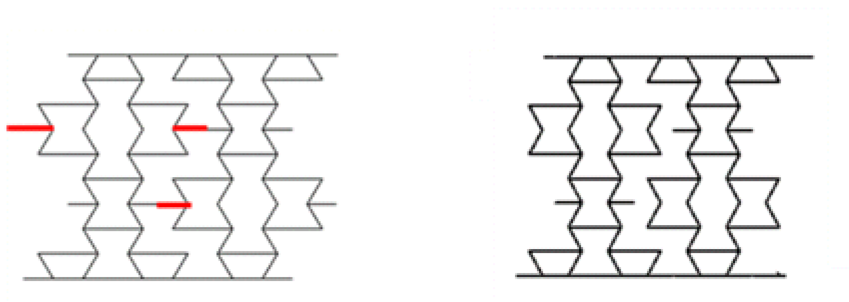


Figure 4.4 Creation of Modified level-1*.

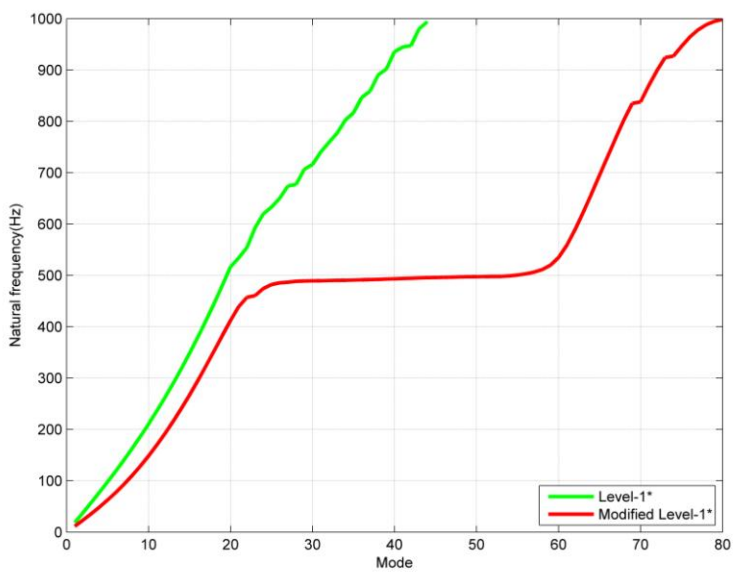


Figure 4.5: Natural frequency plot of zigzag configuration of level-1* and modified level-1*

From Figure 4.5 we can observe that the removal of the connecting links in the structures has resulted in decrease in stiffness at a drastic rate when compared to level-1* structures. When the mode shapes of modified level-1* were inspected it was found that there was

not much change in mode from mode-30 to mode-58 which corresponds to the flat region in the curve.

Table 4.4 presents the natural frequency of single and multi layered level-0 and level-1 structures. From the Figure 4.6, we observe that addition of layers to the level-0 structure increased the natural frequency of the multilayered structure beyond 750 Hz. Initially the multilayered structure was less stiff than the single layered structure. But for the level-1 structure addition of layers decreased the natural frequency throughout the entire frequency range to a small extent. This small change can be due to large number of level-1 honeycomb structures which were already present in the level-0 panel.

Table 4.4: Comparison of first 10 natural frequencies of single and multilayered auxetic honeycomb structures of zigzag configuration

Mode #	Level-0	Level-1	Multi layer L-0	Multi layer L-1
1	27.593	25.343	23.365	23.524
2	55.178	50.854	46.678	47.13
3	84.171	77.883	71.07	71.996
4	112.98	105.35	95.453	97.145
5	141.95	133.71	120.13	122.93
6	171.05	163.08	145.1	149.4
7	200.37	193.68	170.49	176.68
8	229.94	225.63	196.34	204.82
9	259.81	259.05	222.74	233.87
10	290.01	294	249.71	263.87

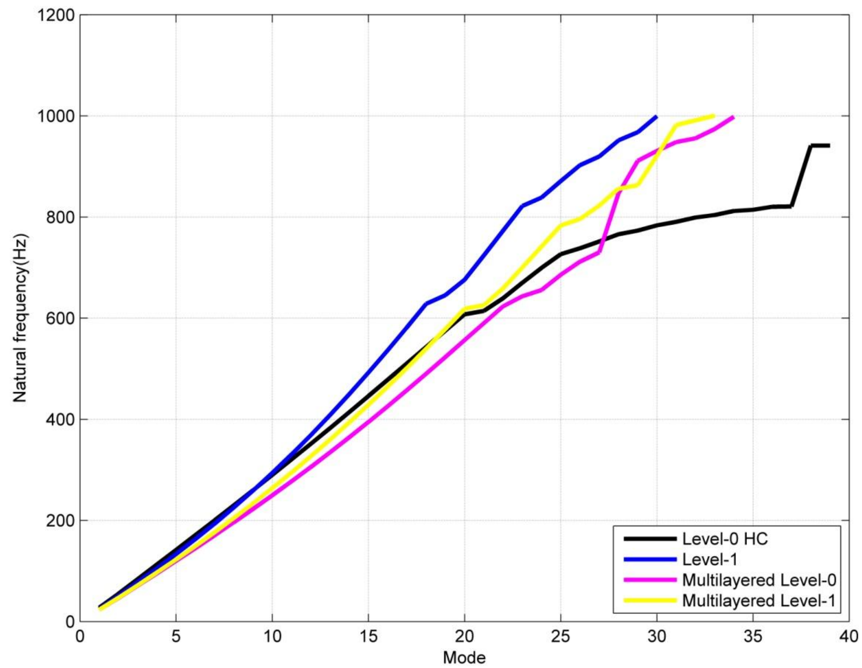


Figure 4.6: Comparison of natural frequency plot of zigzag configuration single layer and multilayered auxetic honeycomb structures

4.2 Natural Frequency of Armchair Configuration Structures

4.2.1 Regular Honeycomb Structures

The Table 4.5 presents the first 10 natural frequencies of armchair configuration single layered regular honeycomb structures. These mode shape are all dilatational in nature except mode number 10 of level-0 structure.

Table 4.5: First 10 natural frequencies of regular honeycomb structures of armchair configuration

Mode #	Level-0	Level-1	Hexagonal corner reinforced	Level-1*
1	62.62	48.896	58.568	58.817
2	129.77	98.617	120.4	120.04
3	205.99	153.96	190.13	189.3
4	283.13	208.99	260.24	258.78
5	360.96	264.16	330.7	328.41
6	439.09	319.23	401.09	397.74
7	517.83	374.49	471.63	467.1
8	597.14	429.94	542.27	536.45
9	677.14	485.74	613.09	605.99
10	757.8	541.92	684.09	675.7

From the Figure 4.7, we identify that the level-1* model is not the least stiff, but the level-1 structures. The level-1 structures is flexible from the initial mode numbers We can see the same trend of shift in rate of change of natural frequency again around the 750 Hz range, with an expectation the Hexagonal corner reinforced structure which shifts the rate of frequency change at around 700 Hz and again at 900 Hz The level-0 and level-1* seem to have similar stiffness up to 800 Hz, after which level-0 structure looses stiffness

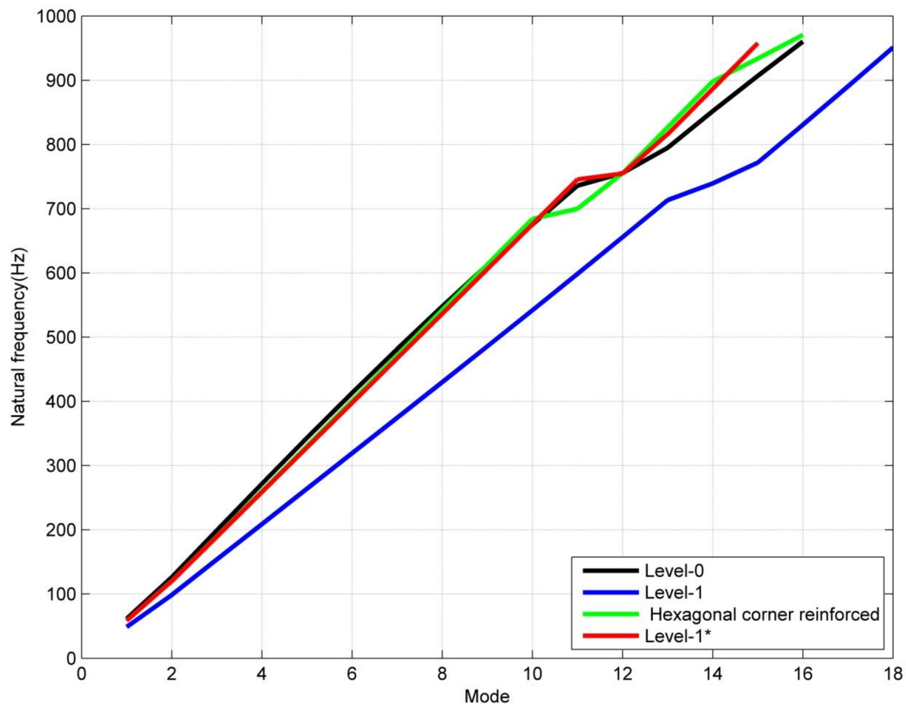


Figure 4.7: Natural frequency plot of armchair configuration single layered regular honeycomb

The Table 4.7 compares the first 10 natural frequencies of single and multilayered armchair configuration regular honeycomb structures. From the Figure 4.8 we observe that the all the structures change the rate in change of natural frequency around 700-750 Hz. Addition of layers to the level-0 structure creates a small increase in natural frequency after mode-11.Increasing the number of layers in the level-1 structures creates a small decrease in the natural frequency throughout the frequency range and this change in stiffness increases as the frequency gets higher.

Table 4.6: Comparison of first 10 natural frequencies of single and multilayered regular honeycomb structures of armchair configuration

Mode #	Level-0	Level-1	Multi layer L-0	Multi layer L-1
1	62.62	48.896	59.214	46.899
2	129.77	98.617	121.41	94.311
3	205.99	153.96	191.63	146.93
4	283.13	208.99	262.09	199.16
5	360.96	264.16	332.74	251.5
6	439.09	319.23	403.19	303.71
7	517.83	374.49	473.77	356.06
8	597.14	429.94	544.5	408.55
9	677.14	485.74	615.54	461.32
10	757.8	541.92	686.95	514.37

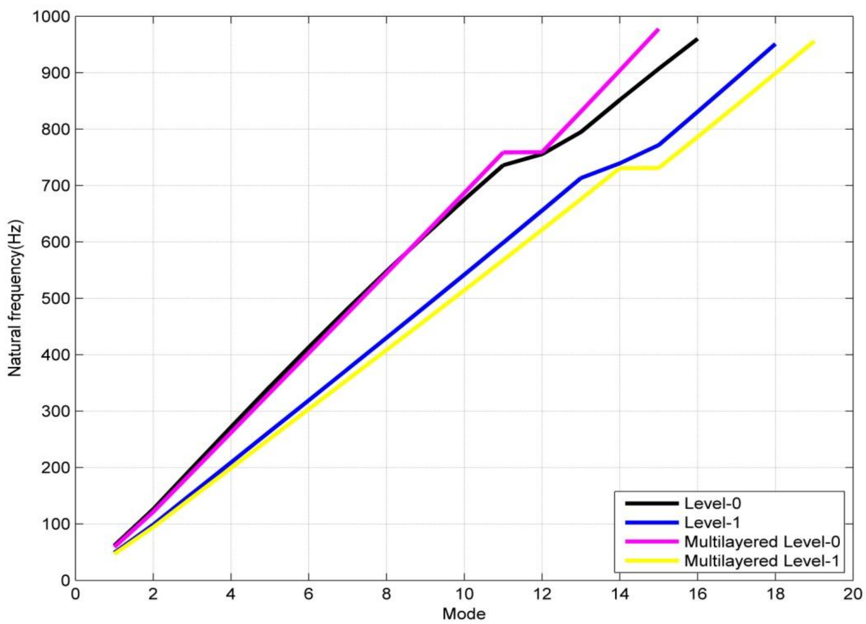


Figure 4.8: Comparison of natural frequency of armchair configuration single layer and multilayered regular honeycomb structures

.4.2.2 Auxetic Honeycomb Structures

The Table 4.7 presents the first 10 natural frequencies of armchair configuration auxetic honeycomb structures.

Table 4.7: Table: First 10 natural frequency of auxetic honeycomb structures of armchair configuration

Mode #	Level-0	Level-1	Rhombic corner reinforced	Level-1 *
1	19.354	19.322	23.344	12.28
2	39.064	38.888	47.795	24.795
3	60.188	59.649	75.055	37.976
4	82.262	81.07	103.61	51.86
5	105.55	103.39	133.33	66.69
6	130.01	126.61	163.82	82.614
7	155.66	150.78	195.09	99.773
8	182.45	175.9	227.08	118.26
9	210.36	202.03	259.9	138.14
10	239.37	229.17	293.56	159.47

We can observe from the Figure 4.9 that the level-1* structure is the only structure with completely low stiffness and the rhombic corner reinforced structure being the stiffest structure throughout the frequency range of interest. We can also observe that the level-1* structure initially changes the rate of natural frequency at 350 Hz and then has steep shift in the plot around the 750 Hz range, beyond which the stiffness goes on reducing. Also the stiffness of level-1 is very close to the level-0 structure. This implies that the addition of hierarchy does not affect the structure drastically in the case of auxetic honeycombs

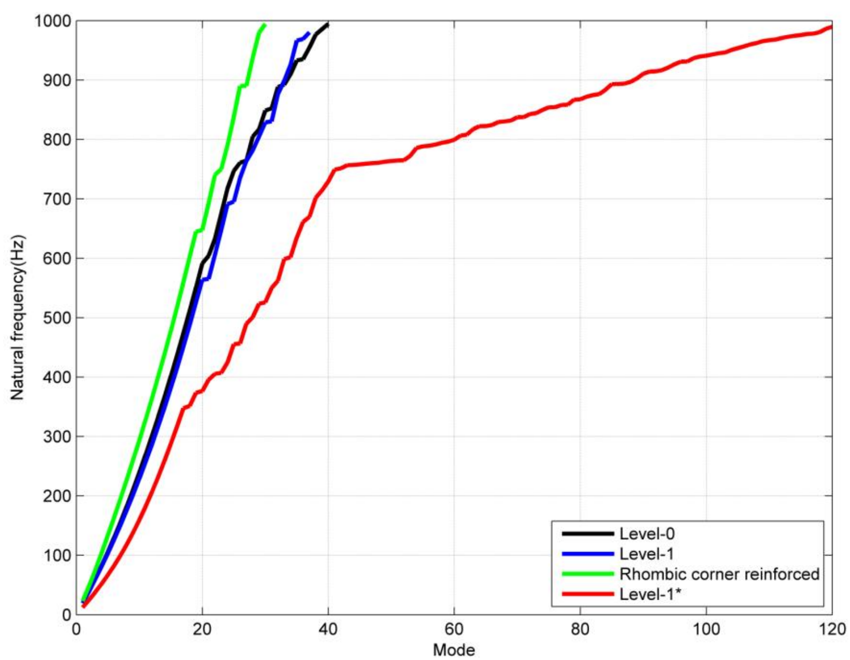


Figure 4.9: Natural frequency plot of single layered armchair configuration auxetic honeycomb structure

The Table 4.8 compares the first 10 natural frequencies of single and multilayered armchair configuration auxetic honeycomb structures

Table 4.8: Comparison of first 10 natural frequencies of single and multilayered auxetic honeycomb structures of armchair configuration

Mode #	Level-0	Level-1	Multi layer L-0	Multi layer L-1
1	19.354	19.322	17.268	17.951
2	39.064	38.888	34.686	36.026
3	60.188	59.649	52.951	54.956
4	82.262	81.07	71.738	74.33
5	105.55	103.39	91.319	94.406
6	130.01	126.61	111.79	115.26
7	155.66	150.78	133.28	137
8	182.45	175.9	155.85	159.7
9	210.36	202.03	179.57	183.44
10	239.37	229.17	204.48	208.26

From Figure 4.10 we identify the single layered structures are actually stiffer than their respective multilayered structure. So addition of multiple layers reduced the natural frequency of both the level-0 and level-1 structures. The natural frequencies were very close to each other up to 150 Hz after which they start to change.

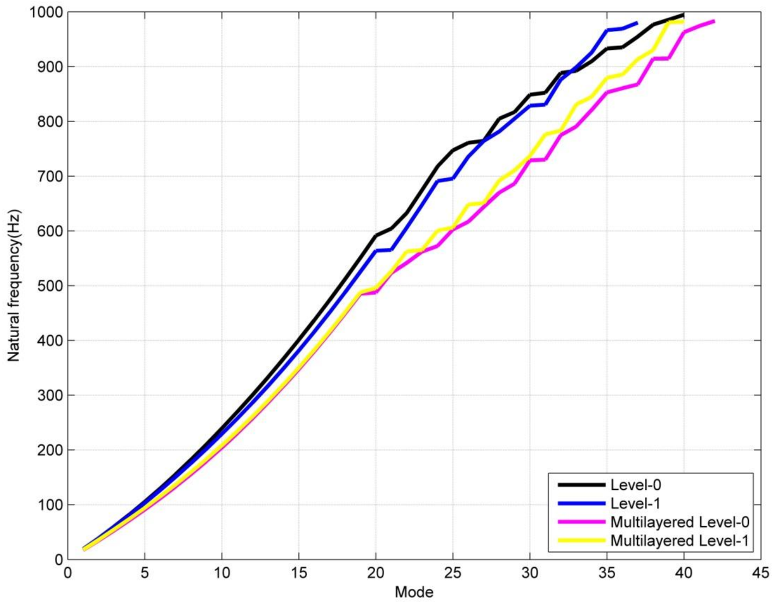


Figure 4.10: Comparison of natural frequency of armchair configuration single layer and multilayered auxetic honeycomb structures

4.3 Mode Shapes

The study of mode shapes is important in structures involving fluid-structure interactions, as the mode shapes represent the spatial representation of natural frequencies. They will help us to understand the impact on the sound radiation. We know that there are two major kinds of mode shapes for honeycomb sandwich panels from previous literature the flexural mode shape and the dilatational mode shape [33, 34, and 35]. The flexural mode shape creates an asymmetrical deformation of the panel, whereas the dilatational mode shape creates a symmetrical deformation of the panel. The flexural modes occur when the wavelength is large and modes change to dilatational mode at shorter wavelengths. The flexural mode shape deforms the structure in the same direction whereas the dilatational deforms the structure in the opposite direction.

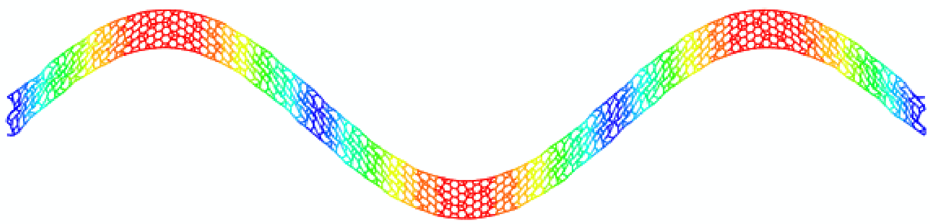


Figure 4.11: Flexural mode shape of level-1 zigzag configuration regular honeycomb at 165.07 Hz

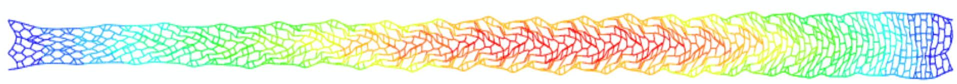


Figure 4.12: First Dilatational mode shape of level-1 zigzag configuration regular honeycomb at 748.68 Hz

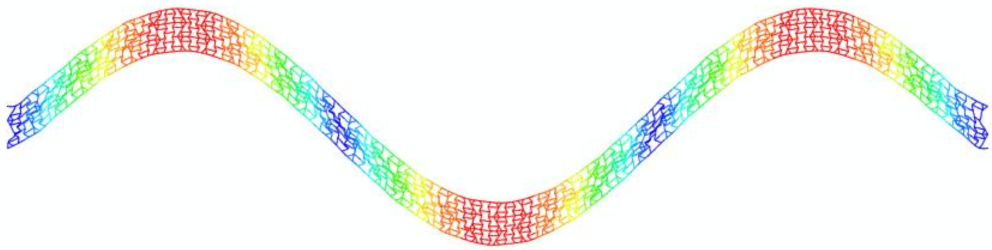


Figure 4.13: Flexural mode shape of level-1 zigzag configuration auxetic honeycomb at 77.883 Hz

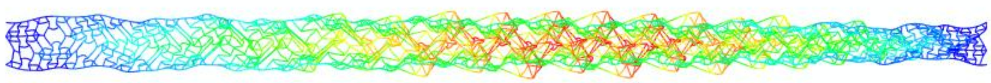


Figure 4.14: First Dilatational mode shape of level-1 zigzag configuration auxetic honeycomb at 645.45 Hz

By comparing the frequency at which the dilatational mode shapes occur and natural frequency plot for a regular honeycomb model of zigzag configuration, we can observe that the step change in the plot is caused by the occurrence of the first dilatational mode at 755.58 Hz and similarly for the auxetic model we can observe the steep change in the plot at 614.45 Hz. The Figure 4.11-4.14 present the flexural and dilatational mode shapes of zigzag configuration. This change in rate of natural frequency at the occurrence of first dilatational mode is also seen in the armchair configuration.

4.31 SPECIAL CASES OF MODE SHAPES

Figure 4.15 shows the first dilatational mode shape of level-1* structure which occurs around 534.23 Hz. As the stiffness of the structure decreases the first dilatational mode shape also begins to appear at occurs at lower frequencies. We can also observe that this mode shape resembles the dilatational mode shape of level-1 structure.

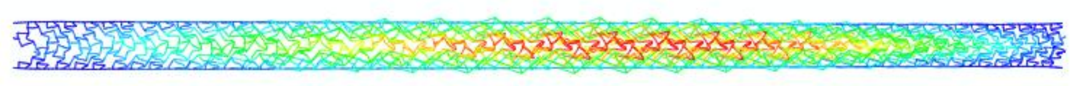


Figure 4.15 First dilatational mode shape of zigzag configuration auxetic structure at534.23 Hz

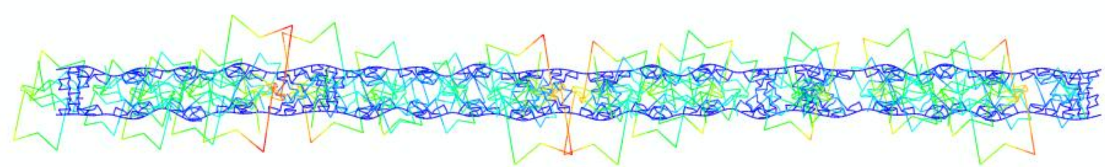


Figure 4.16 Mode-30 of Modified Level-1* structure at 489.51 Hz

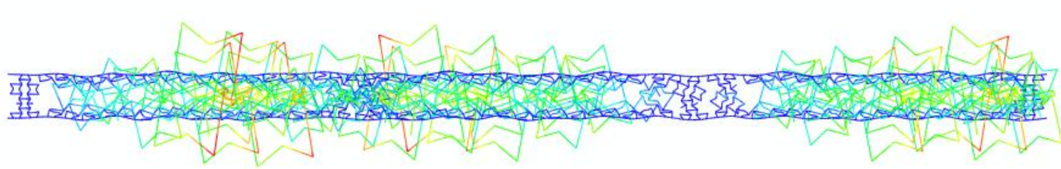


Figure 4.17 Mode-45 of Modified Level-1* structure at 495.58 Hz

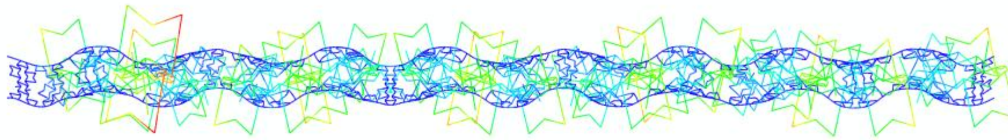


Figure 4.18 Mode-55 of Modified Level-1* structure at 500.77 Hz

Figure 4.16-4.18 represent the mode shapes of modified level-1* structure which occur in the flat region of the natural frequency curve in Figure 4.4. From the mode shapes we can observe that there is not much change in the flexural mode shape for almost 30 modes.

In Figure 4.19 the first dilatational mode shape of armchair configuration auxetic level-1* structure is shown. This mode shape corresponds to the first steep change in the natural frequency curve. The mode shape shown in Figure4.20 corresponds to the steep shift in the rate of change of natural frequency at 750 Hz.

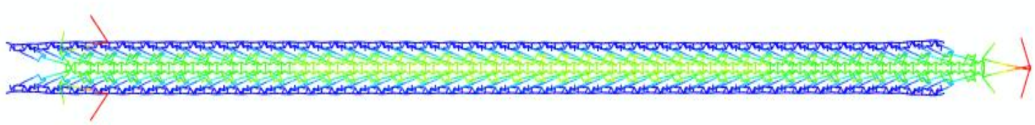


Figure 4.19 Mode-18 of Level-1* auxetic structure of armchair configuration at 351.6 Hz

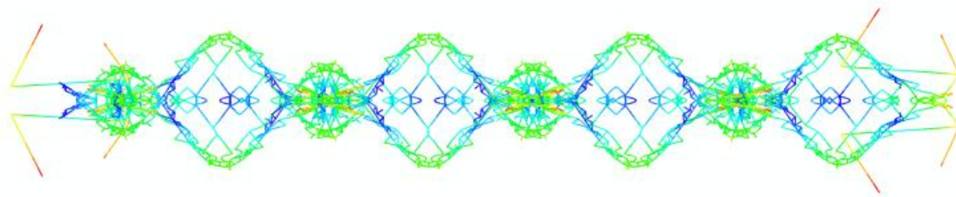


Figure 4.20 Mode-42 of Level-1* auxetic structure of armchair configuration at 751.34 Hz

CHAPTER-5

RESULTS AND DISCUSSION

The results of the analysis from Abaqus are collected and plotted in mat lab. The plots show the transmitted sound pressure level variation for a frequency range of 0~1000 Hz for all the structures.

5.1 Zigzag Configuration Regular Honeycomb structure

In this section the results of zigzag configuration structures will be discussed.

5.1.1 Level-0 Honeycomb

The plot in Figure 5.1 shows the variation of sound pressure level of the nodes which are in the contact with the air. We can see the steep rise in the pressure level corresponding to the odd modes. In order to quantitatively compare the sound pressure level for various structures, the area under the curve is calculated.

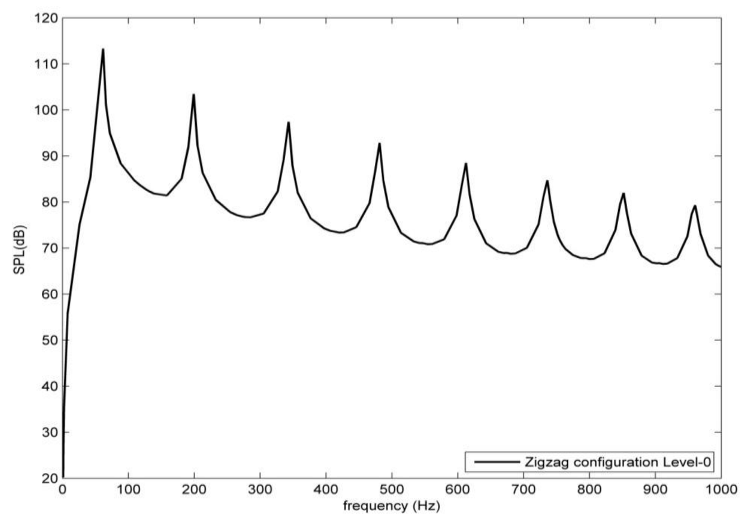


Figure 5.1: Sound pressure level of zigzag configuration level-0 regular honeycomb

The area under the curve for this structure is 76743 dB.Hz. But in order to increase the accuracy of the measurement we exclude the first 100 Hz which results in a value 67737 dB.Hz. The sound pressure level generated during the first 100 Hz is due to the stiffness of the plates and it corresponds to the stiffness region of sound transmission loss curve and so it is excluded.

The sound transmission loss curve for the level-0 honeycomb is shown in Figure 5.2. The sound transmission loss has same number of dips as the number of peaks for the sound pressure level curve at the exact frequency.

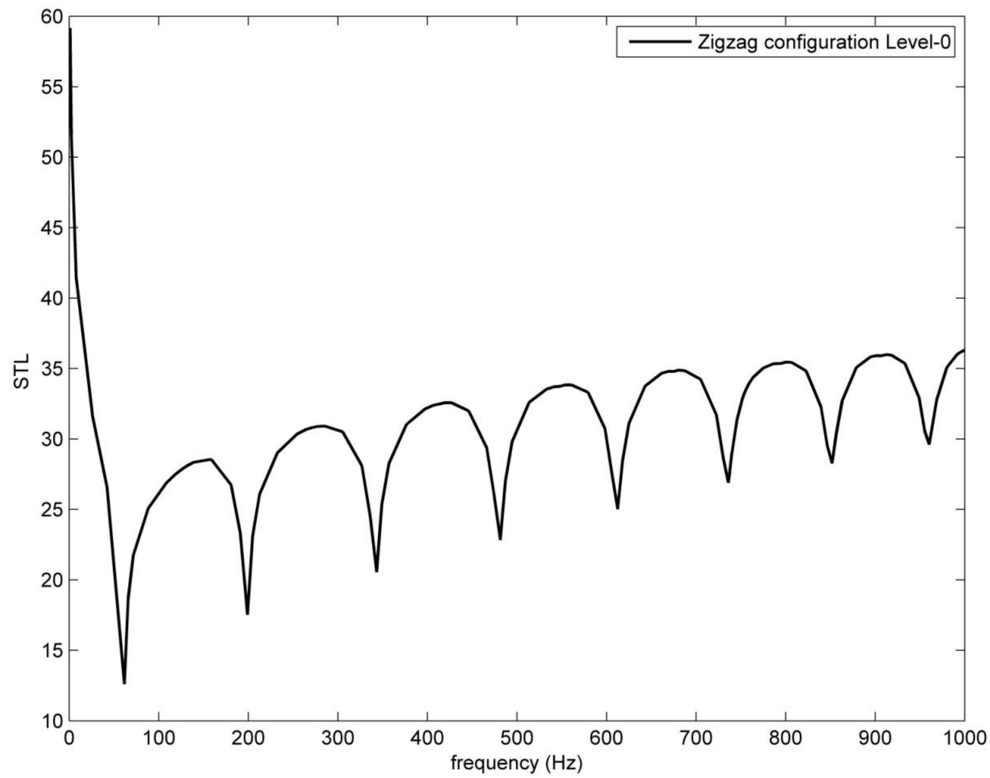


Figure 5.2: Sound transmission loss curve of zigzag configuration level-0 regular honeycomb

5.1.2 Level-1 Honeycomb

The plots shown in Figure 5.3 represent the sound pressure level for a level-1 hierarchy honeycomb. The area under the curve of level-0 honeycomb excluding the first 100 Hz was 67737 dB.Hz, while the area under the curve of level-1 honeycomb was 66314 dB.Hz. Thus there is a decrease of 2.1 % of sound pressure level from a level-0 honeycomb to level-1 honeycomb. It is to be noted that the thickness of the level-0 and level-1 are kept uniform for each structure in this study and the thickness of face plate thickness is same for all the structures.

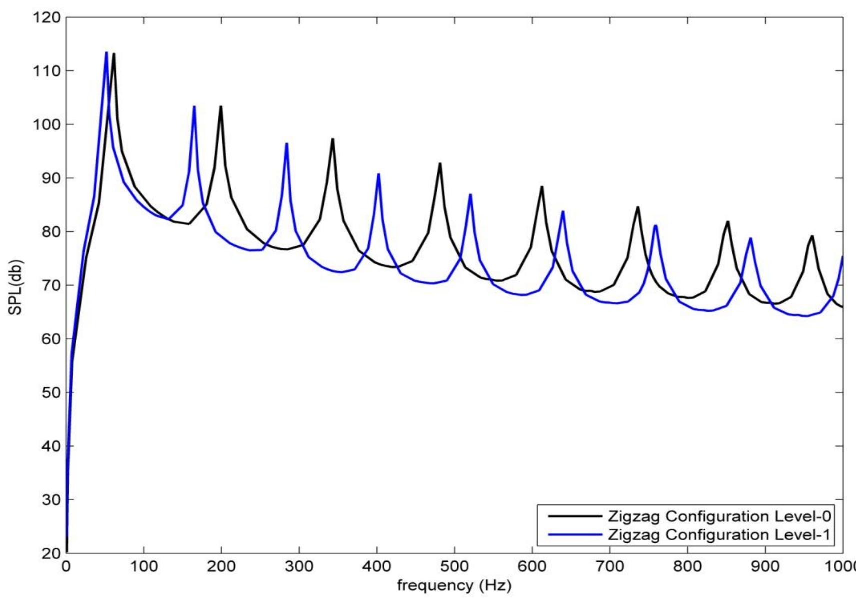


Figure 5.3: Comparison of sound pressure levels between level-0 and level-1 honeycomb

We observe a reduction of stiffness for level-1 hierarchical honeycomb from the Figure 5.3. This is clearly shown by the shifting of the peaks towards the left for level-1 honeycomb in the resonance controlled region.

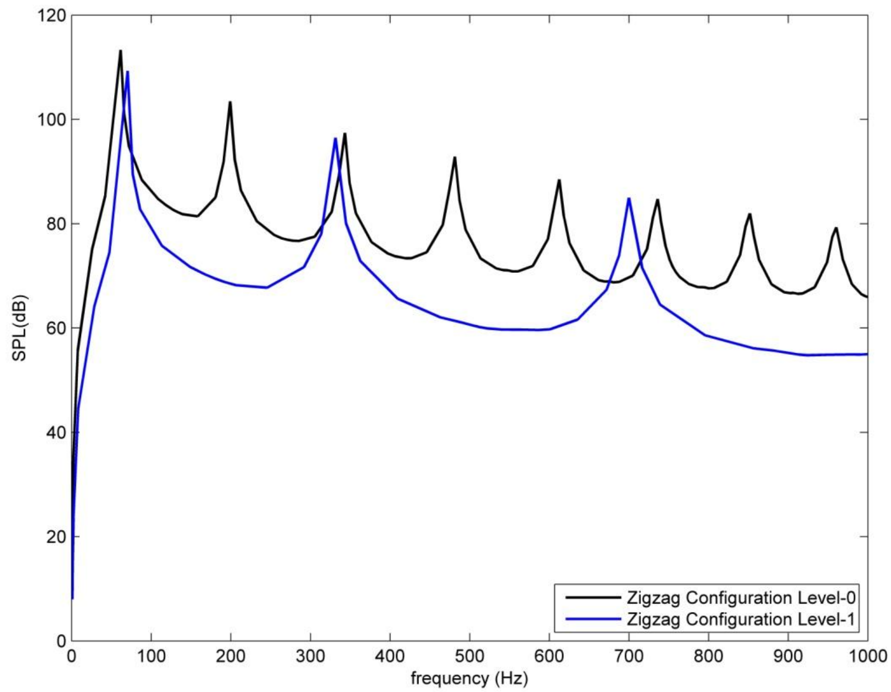


Figure 5.4: Comparison of sound pressure levels between level-1 and level-0 structures with constant thickness of 3.1 mm

The plot shown in Figure 5.5 compares the level-0 and level-1 hierarchy honeycomb with same thickness for the both the structures. As we have used the same thickness value for level-1 and level-0, the mass of level-1 honeycomb had increased to 207 kg, whereas the mass of level-0 structures was 73.96 kg. This increase in mass causes an increase in stiffness. This is seen by the shift of the peaks of level-1 honeycomb towards the right

with respect to the peaks of level-0 honeycomb. Another important observation is that the level-1 honeycomb transmits less sound than the level-0.

5.1.3 Level-2 Honeycomb

The comparison of level-1 honeycomb and level-2 honeycomb in Figure 5.5 reveals that the second order of hierarchy does not influence the sound transmission property to a very great extent. This may be due to the highly reduced thickness of level-1 and level-2 hierarchical honeycomb. The reduced thickness of level-1 and level-2 honeycomb does change the overall stiffness to a very small extent, hence the small shift in the frequency. Again it is to be noted that the thickness of the level-0 and level-1 hierarchy honeycombs in the structure are maintained uniform for honeycombs belonging to each level of hierarchy. When we compared the area under the curve excluding the first 100 Hz for level-1 and level-2 HC we found a percentage difference of 0.63, with level-2 transmitting less sound pressure than level-1.

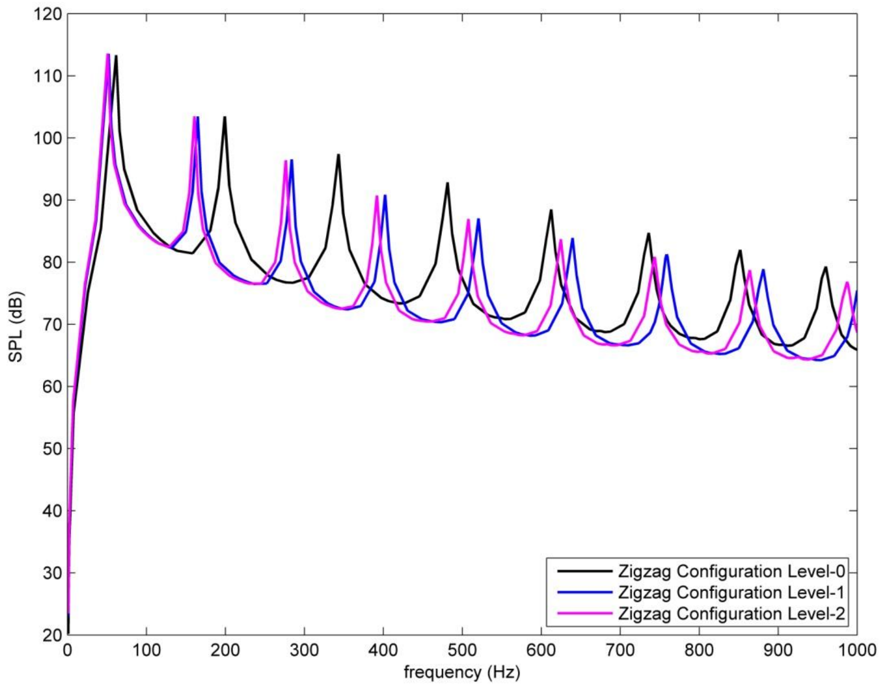


Figure 5.5: Comparison of sound pressure level between level-0, level-1 and level-2 honeycomb

5.1.4 Effect of Thickness Ratio between Various Levels of Hierarchy

The ratio of the thickness of level-0- honeycomb to the thickness of level-1 honeycomb on the sound transmission is studied and the results are given in Figure 5.6. In this experiment the thickness of the level-0 and level-1 honeycomb are varied in a ratio, with the thickness of the level-0 used as the reference. We can see that the shift of the peaks for ratio-0.5(L1/L0=0.5) structure is large compared to shift of peaks for ratio-2(L1/L0=2) structure, considering ratio-1 as the reference. Therefore doubling the thickness of level-0 structures reduces the stiffness of panel. This change is stiffness is prominent from the Figure 5.6. But doubling the thickness of level-1 structure increased

the stiffness, but this stiffness change is not very prominent. In all the three cases the sound pressure level does not change radically though it is the least for Ratio-0.5 structure. Therefore increasing the ratio increased the stiffness and decreasing the ratio reduced the thickness.

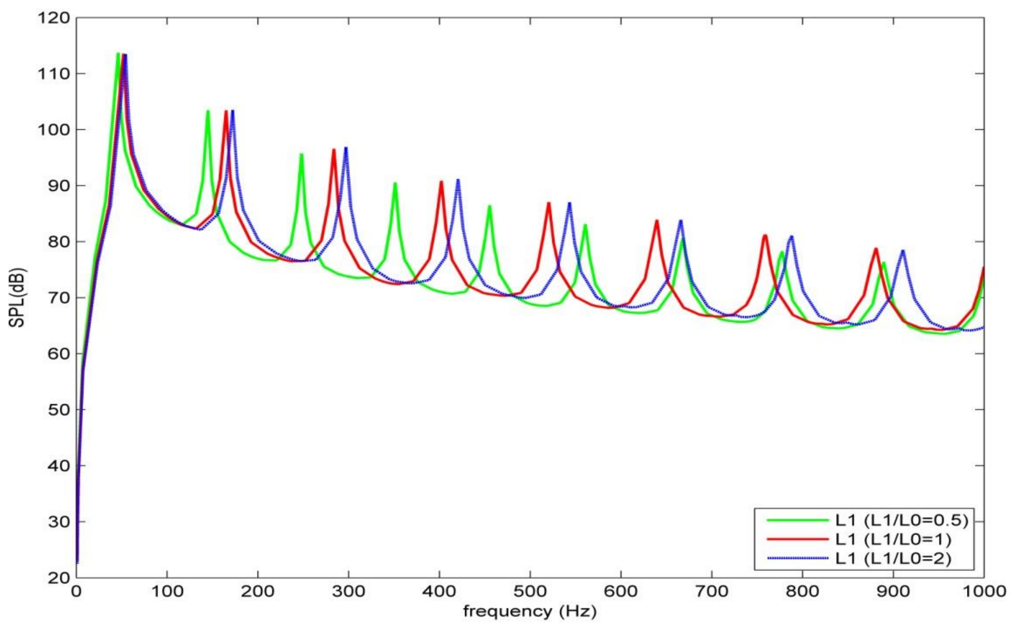


Figure 5.6: Comparison of zigzag configuration level-1 honeycomb with different thickness ratio

5.1.5 Effect of Hexagonal Corner Reinforcement

A study was conducted to study the effect of the corner reinforcements. The corner reinforced structure was compared to level-0 honeycomb and a structure with no hierarchy at all called the level-1* structure. From the Figure 5.7, we can see that the level-0 honeycomb structure closely resembles the corner reinforced structure. In Figure

5.8 the level-1* structure and the corner reinforced structure were compared. It was found that hexagonal corner reinforced structure was less stiff than the level-1*structure. This proves the absence of hierarchy decreases the stiffness. But there were lots of irregularities in the frequency response as the frequency got higher which is attributed to the trim effect.

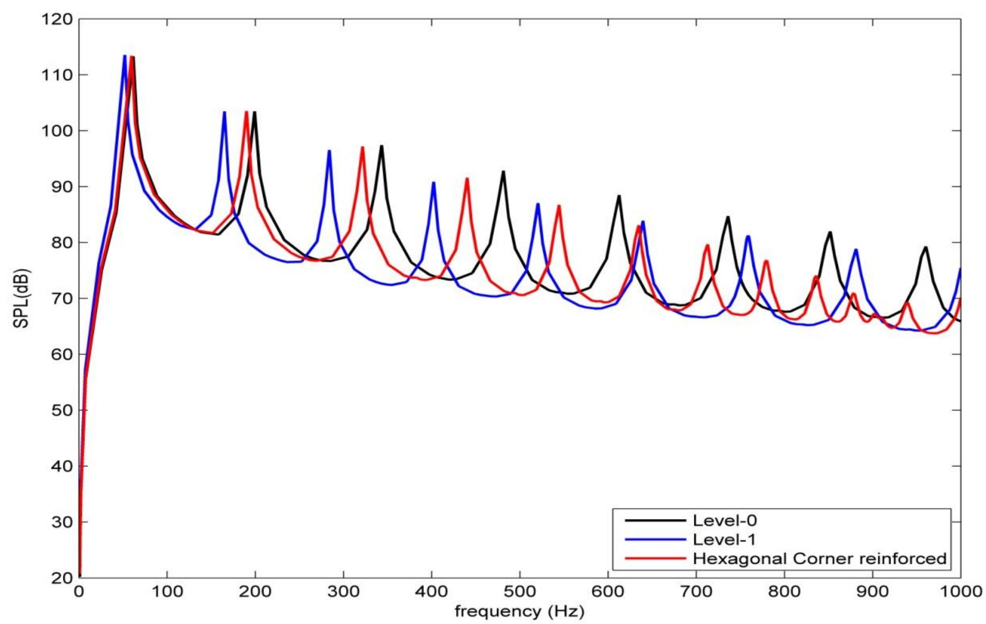


Figure 5.7: Comparison of zigzag configuration corner reinforced structure with level-0 and level-1 honeycomb

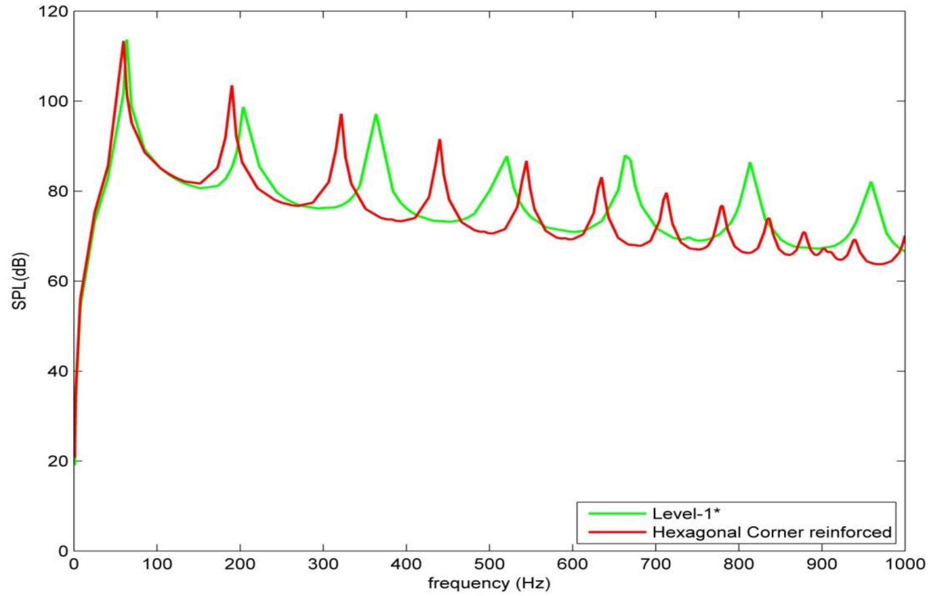


Figure 5.8: Comparison of zigzag configuration hexagonal corner reinforced structure with level-1* structure

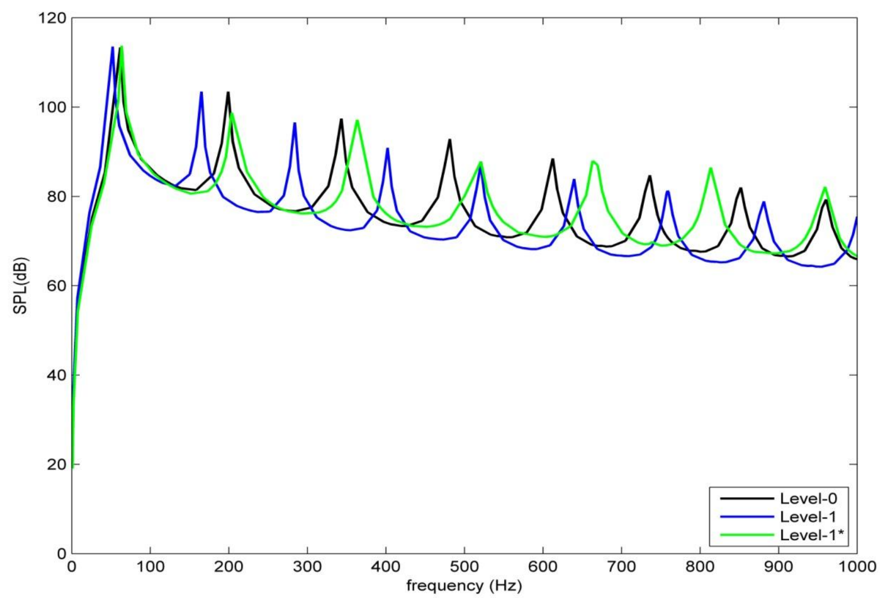


Figure 5.9: Comparison of zigzag configuration level-1* with level-0 and level-1 structure

From the Figure 5.9 we can observe that level-1* has a similar sound transmission property of level-0 honeycomb than level-1 honeycomb. The comparison of level-0 and hexagonal corner reinforced plot showed that the corner reinforced structure is less stiff than the level-0 honeycomb structure. But the level-1* was much stiffer than the level-1 structure up to 500 Hz, after which the stiffness increased rapidly. We conclude that the corner reinforcement does not change the sound transmission property to a very great extent, but reduced the stiffness of the structure primarily because of the absence of level-1 hierarchy.

5.1.6 Multilayered Regular Honeycomb Structures

The multilayered study is done to nullify the influence of boundary effects on the acoustical properties.

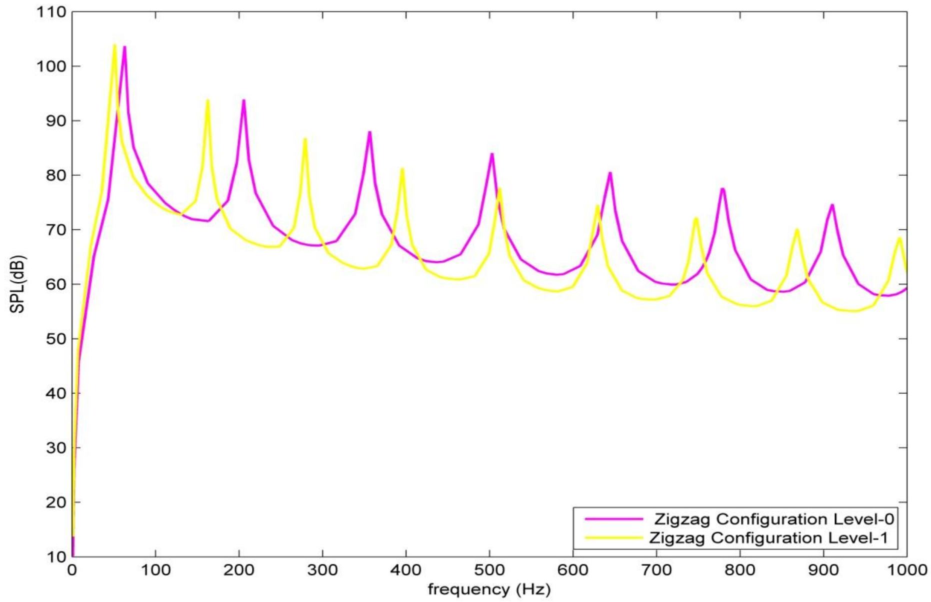


Figure 5.10: Comparison of zigzag configuration multilayered level-0 and level-1 honeycomb

We find that the multilayered level-1 honeycomb structure is also less stiff than the level-0 honeycomb structure. In fact the reduction in stiffness is very evident as the peaks have shifted enough to accommodate two more peaks within the 1000 Hz in the Figure 5.10. Also there is considerable reduction in the sound pressure level transmitted when the single and multilayered level-0 and level-1 honeycombs are compared respectively. The plots in Figure 5.11 and 5.12 do not match even in the stiffness controlled region. Another important observation is the level-1 multilayered honeycomb has the almost the same stiffness as the single layered structure up to 400 Hz.

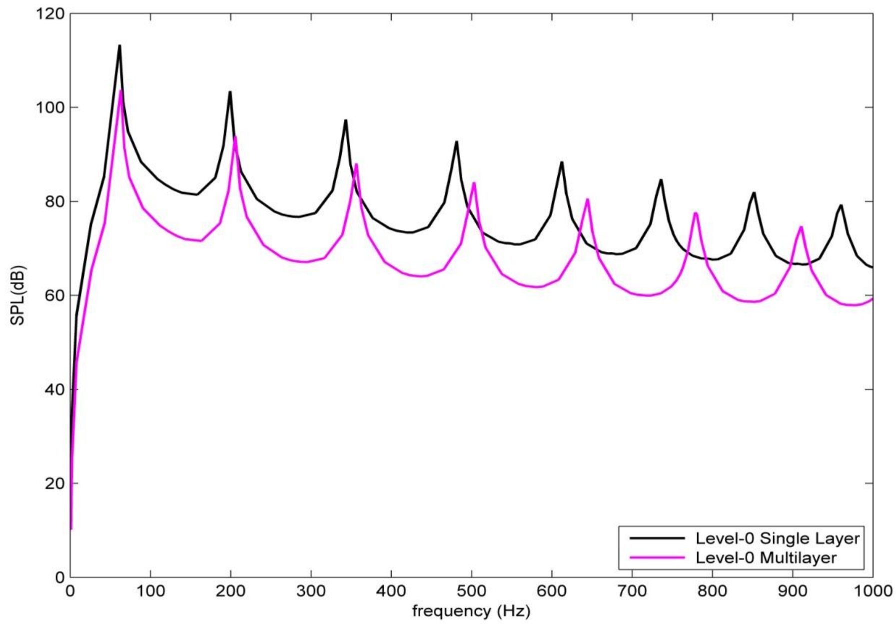


Figure 5.11: Comparison of zigzag configuration single layered and multilayered level-0 honeycombs

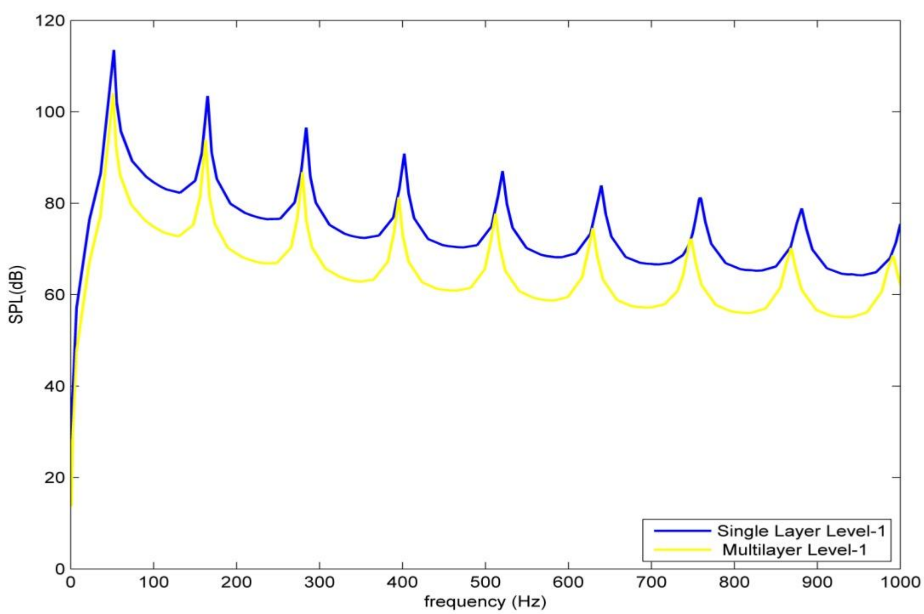


Figure 5.12: Comparison of zigzag configuration single layered and multilayered level-1 honeycombs

A special case of the multilayered structures was studied to find the effect of adding additional layers to the already existing layers. The structure used for the study is shown in Figure5.13 and was created by adding half layer of honeycomb on top of the existing multilayered structure. This structure is compared with single layered level-0 and multilayered level-0 structure.

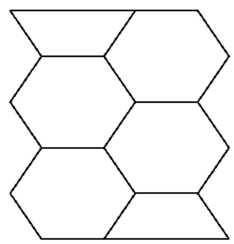


Figure 5.13 Two and half layered zigzag orientation regular honeycombs structure

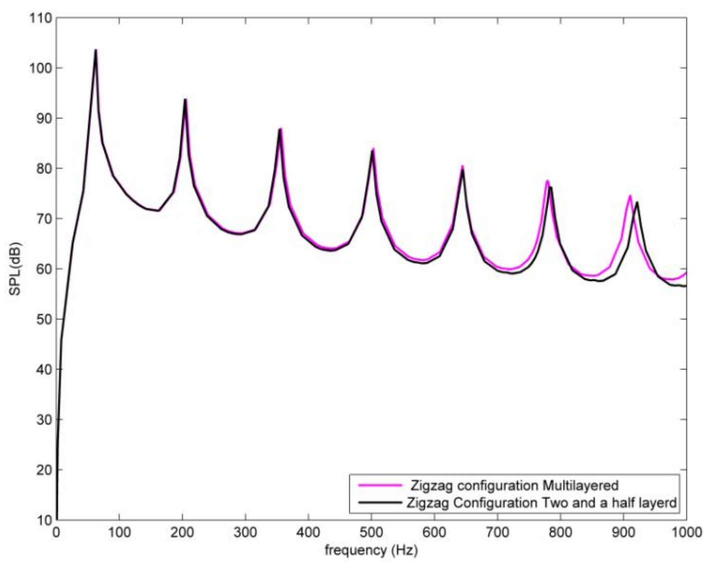


Figure 5.14 Comparison of zigzag configuration multilayered and two and a half layered structure

From Figure 5.14 we can observe that addition of another half layer did not affect the sound transmission property of the multilayered structure up to 700 Hz beyond which it increases the stiffness of the structure.

5.1.7 Comparison of Sound Transmission of Regular Honeycomb Structures

The Table 5.1 provides the sound pressure levels which are compared based on the area under the curve of the respective structures and the plot in Figure 5.15 is created using the area under the curve excluding the first 100 Hz values. We can observe that there is not much change in sound pressure level among the single layered structures.

Table 5.1: Sound pressure level of zigzag configuration regular honeycomb structures

Structure	Area under the curve (dB.Hz)	Area under the curve Excluding first 100 Hz(dB.Hz)	% Decrease(Reference Value: L0 HC)
Level-0	76743.00	67737.00	
Level-1	74576.00	66314.00	2.10
Level-2	74501.00	65891.00	2.73
Corner reinforced	75309.00	66634.00	1.63
Level-1*	75890.00	67304.00	0.64
Multilayered L-0	67993.00	59805.00	11.71
Multilayered L-1	65176.00	57948.00	14.45

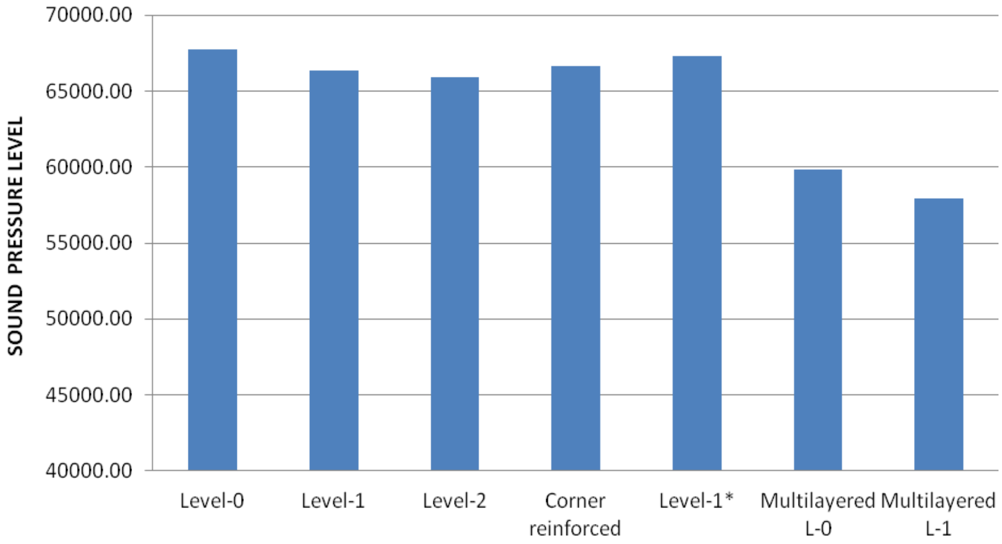


Figure 5.15: Sound pressure level of zigzag configuration regular honeycomb structures

5.2 Zigzag Configuration Auxetic Honeycomb Structures

In this section the results of zigzag configuration auxetic structures will be discussed.

5.2.1 Level-0 Honeycomb

The frequency response of level-0 auxetic honeycomb is shown in Figure 5.16. The area under the curve excluding first 100 Hz is 63704 dB.Hz. We can see a peak at 950 Hz. This can be due to shifting of double wall frequency to lower frequencies or coincidence effect.

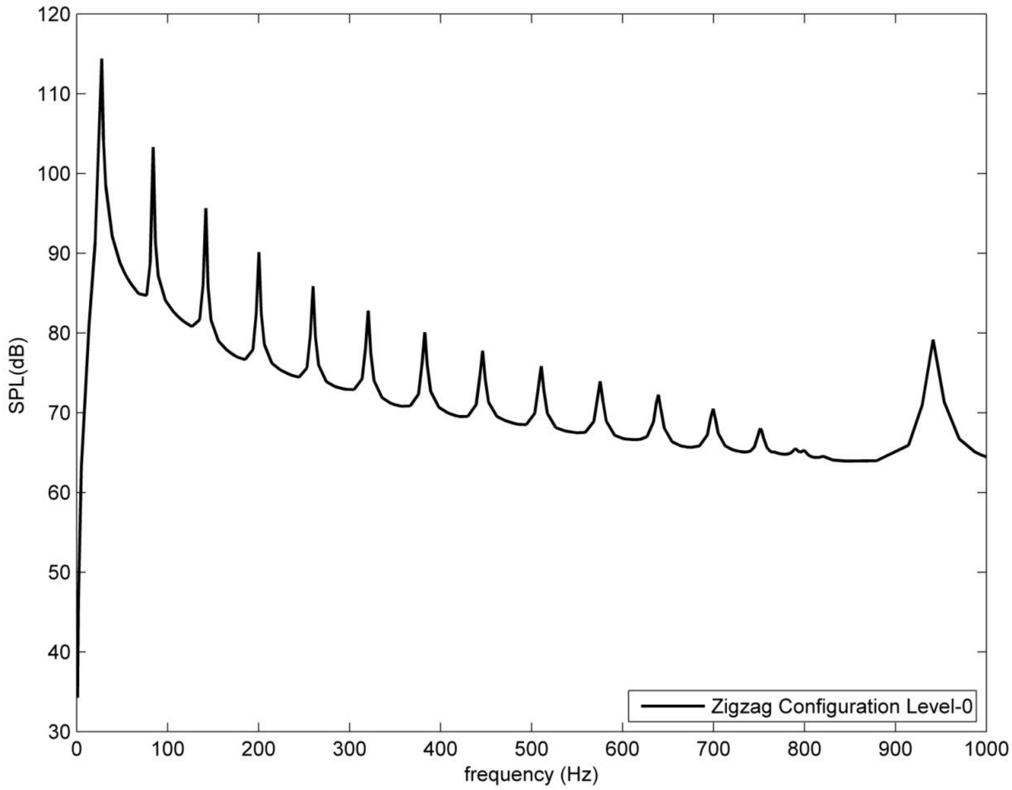


Figure 5.16: Sound pressure level of Zigzag configuration auxetic level-0 honeycomb

5.2.2 Level-1 Honeycomb

The Level-1 auxetic structure show in Figure 5.17 has evenly spaced peaks in the rear end of the frequency spectrum which was not seen in level-0 auxetic honeycomb. The area under the curve for level-1 auxetic honeycomb excluding the first 100 Hz is 63064 dB.Hz. We can also observe that the hierarchy has caused the tall peak to shift further beyond the target frequency range,i.e, 1000 Hz.

The sound pressure level varies by 1 % between level-0 and level-1, with level-1 honeycomb transmitting less sound compared to level-0 honeycomb. We can observe that

the level-1 honeycomb changes its stiffness characteristics from around 250 Hz. Initially the stiffness of the level-0 and level-1 honeycomb is same and then it starts to decrease, which is evident from the shift of peaks towards the left till 250 Hz. And again the stiffness matches at 250 Hz .But moving further along the frequency we can see that the stiffness starts to increase gradually. This could be the reason why we don't observe the tall peak which was observed for level-0 structure.

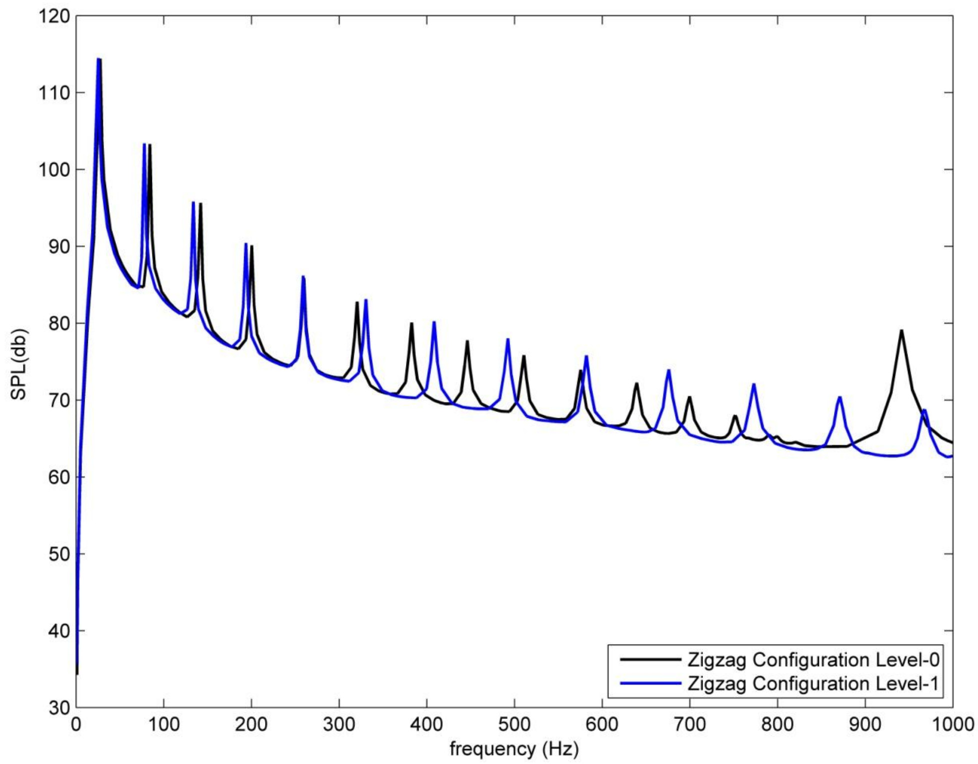


Figure 5.17: Comparison of zigzag configuration auxetic level-0 and level-1 honeycomb

5.2.3 Effect of Rhombic Corner Reinforcement

In order to study the effect of corner reinforcement a comparison is done between a rhombic corner reinforced honeycomb, level-0 and level-1 auxetic honeycomb, which is shown in Figure 5.18. It is clear that the sound pressure level curve of rhombic corner reinforced auxetic honeycomb matches comparatively closer to the level-1 auxetic honeycomb than the level-0 auxetic honeycomb. Another important observation is that the auxetic rhombic corner reinforced is initially stiff till 500 Hz and then it becomes more flexible than the level-1 auxetic honeycomb. The rhombic corner reinforcement increases the stiffness of the structure up to certain frequency and then reduced it drastically.

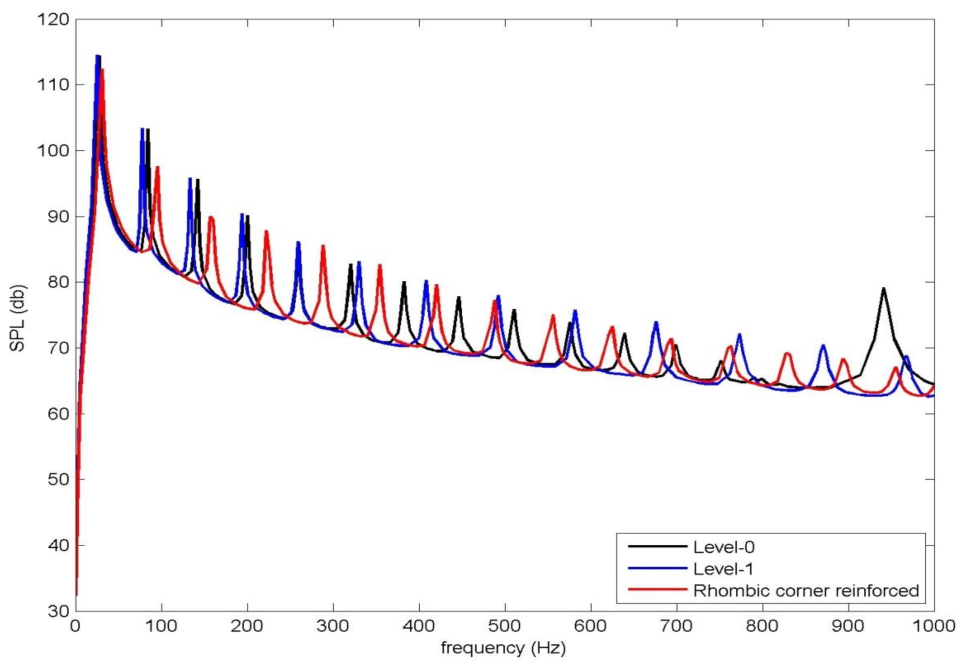


Figure 5.18: Comparison of zigzag configuration auxetic level-0, level-1 and rhombic corner reinforced honeycomb

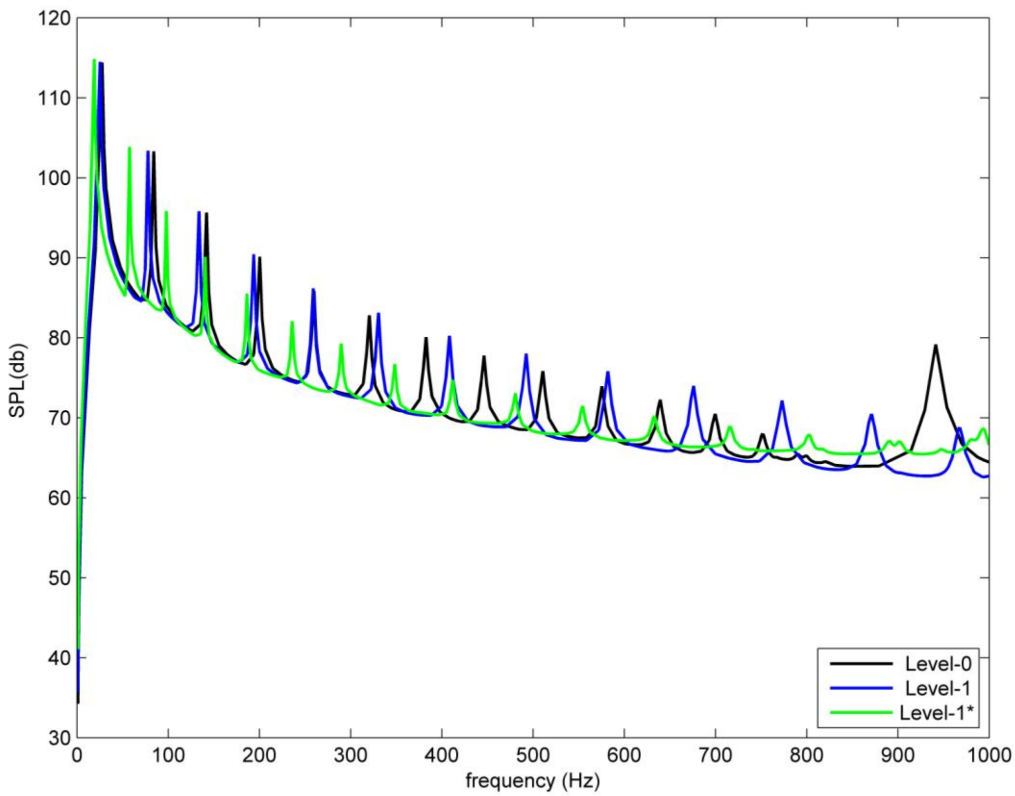


Figure 5.19: Comparison of zigzag configuration auxetic level-0, level-1 and level-1* honeycomb

From Figure 5.19 we observe that level-1* reduces the stiffness of the structure. Form Figures 5.18, 5.19 and Figure 5.20 comparison we can conclude that the rhombic corner reinforcement increases the stiffness of that structure. In Figure 5.20 we observe that the level-1* is less stiff than the rhombic corner reinforced.

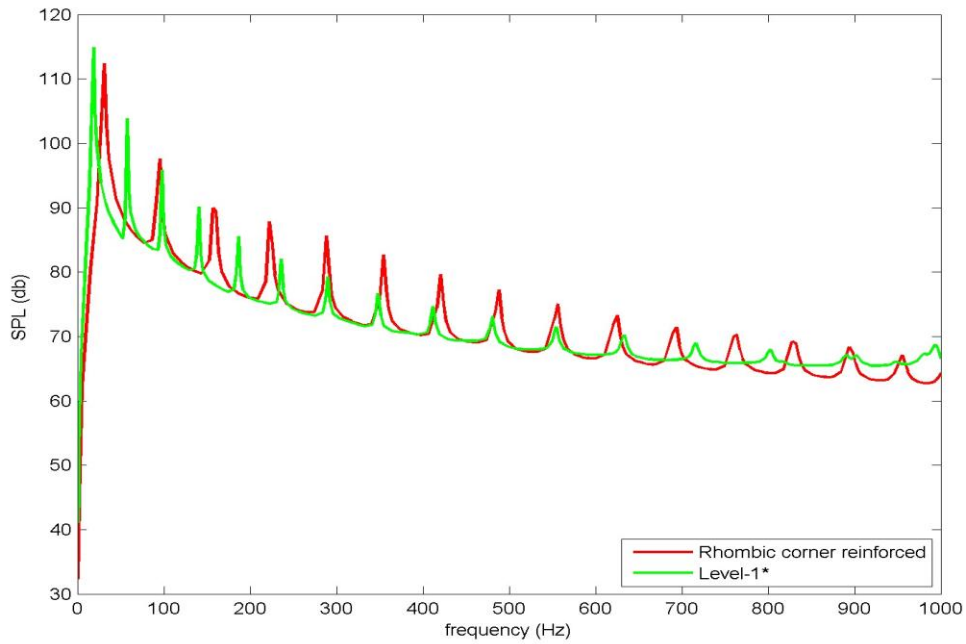


Figure 5.20: Comparison of zigzag configuration auxetic corner reinforced and level-1* honeycomb

5.2.4 Effect of Thickness Ratio between Various Levels of Hierarchy

The thickness of the level-0 honeycomb contributes to a large portion of the overall stiffness of the structure compared to the thickness of the level-1 honeycomb. This can be seen from the shift of the peaks in the plot shown in Figure 5.21. For a ratio-0.5 structure the shift of the peak from the peaks of ratio-1 structure is high in comparison with peaks of ratio-2 structure. As the mass is constant for all the three structures, this proves that the thickness of level-0 honeycomb have more control over the stiffness of the structure. The natural frequencies are reduced for the ratio-2 structure which is a result of reduced thickens of cells belonging level-0 structure. Thus increasing

the ratio reduced the stiffness of the structure, but reducing the ratio did not increase the stiffness.

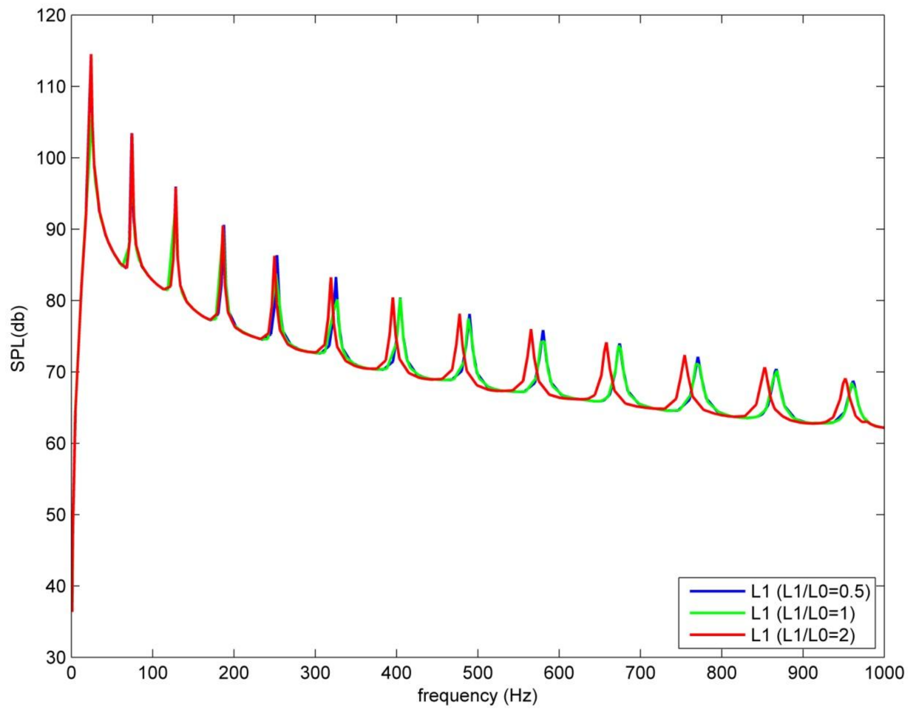


Figure 5.21 Comparison of zigzag configuration level-1 honeycomb with different thickness ratio

5.2.5 Multilayered Honeycomb Structures

As discussed earlier the multilayered analysis is done to exclude the influence of boundary effects in the sound transmission of the structures. Initially multilayered level-0 and level-1 auxetic honeycomb panel are compared. A drastic increase in the sound transmitted is seen in Figure 5.22. Level-1 structure is transmitting more sound that the level-0 structure.

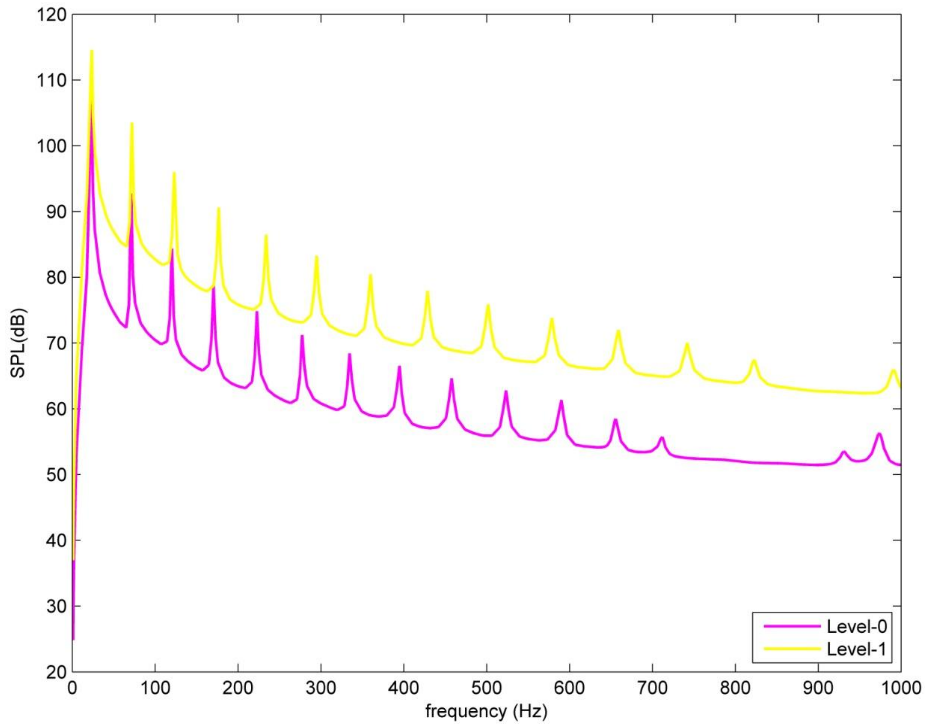


Figure 5.22 Comparison of zigzag configuration multilayered level-1 honeycomb with level-0 honeycomb

Again from Figure 5.23 it is observed that there is a radical reduction in the sound transmitted when a single and multilayered level-0 honeycombs structure is compared. This reduction in sound transmission could be attributed to the symmetry being formed in the structure. In both the models with reduced sound transmission there are two layers of honeycomb in the structure. But this phenomenon is not seen in the level-1 comparison involving the single and multilayered structures in Figure 5.24.

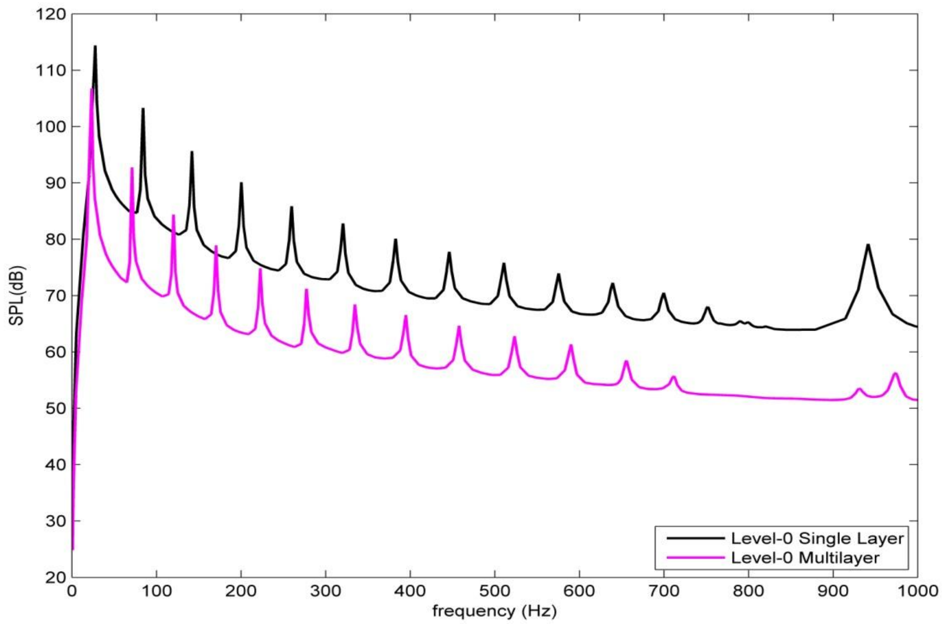


Figure 5.23 Comparison of zigzag configuration level-0 single and multilayered honeycomb

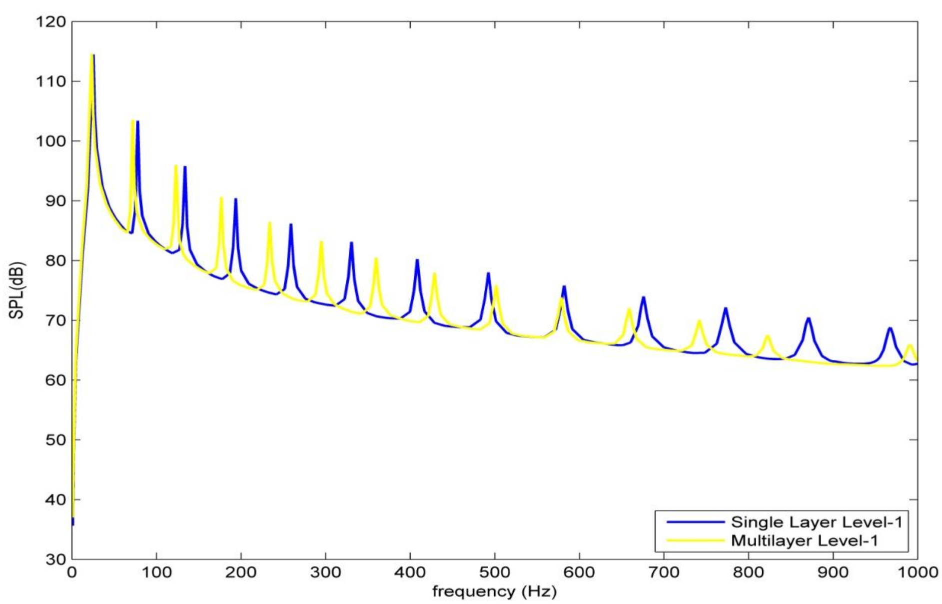


Figure 5.24 Comparison of zigzag configuration level-1 single and multilayered honeycomb

5.2.6 Comparison of Sound Transmission of Auxetic Honeycomb Structures

The Table 5.2 given below provides the sound pressure levels transmitted for various core geometries of auxetic structures of zigzag configuration. The sound pressure levels are measured using the area under the curve of the respective plots of various structures. The Figure 5.25 is created using the area under the curve values which exclude the first 100 Hz.

Table 5.2: Sound pressure level of zigzag configuration auxetic honeycomb structures

Structure	Area under the curve (dB.Hz)	Area under the curve Excluding first 100 Hz(dB.Hz)	% Decrease(Reference Value: L0 HC)
Level-0	72120.00	63704.00	
Level-1	71586.00	63064.00	1.005
Corner reinforced	71854.00	63155.00	0.862
Level-1*	71710.00	62863.00	1.320
Multilayer L-0	59296.00	51850.00	18.608
Multilayer L-1	71216.00	62657.00	1.644

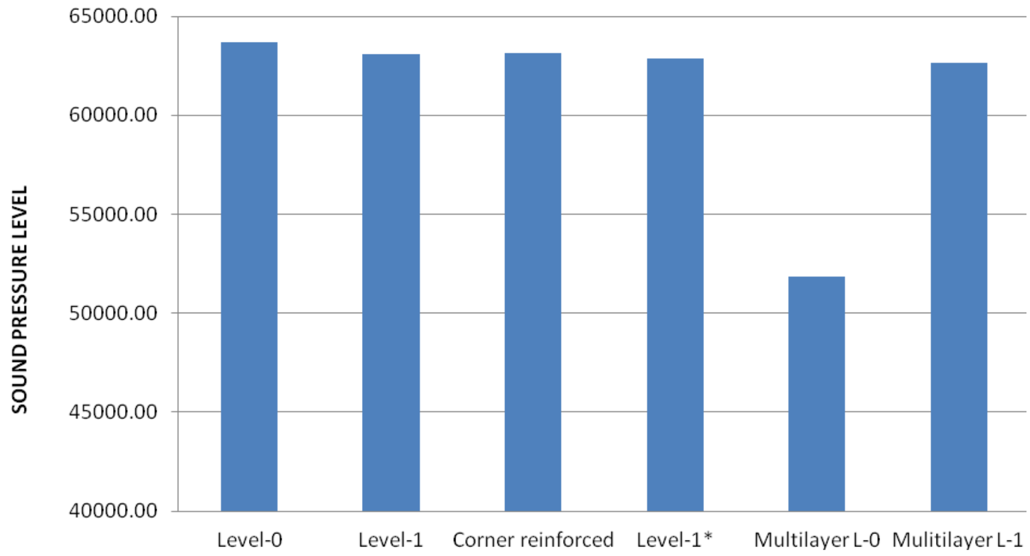


Figure 5.25: Sound pressure level of zigzag configuration auxetic honeycomb structures

5.3 Armchair Configuration Regular Honeycomb Structures

In this section the sound transmission results of regular armchair configuration structures will be discussed.

5.3.1 Level-0 Honeycomb

The level-0 honeycomb structure is used as the reference structure for further comparison. This configuration is one of the most commonly used configurations. The plot given in Figure 5.26 shows the sound pressure level transmitted for the level-0 honeycomb of armchair configuration. It is very similar to the zigzag configuration structure.

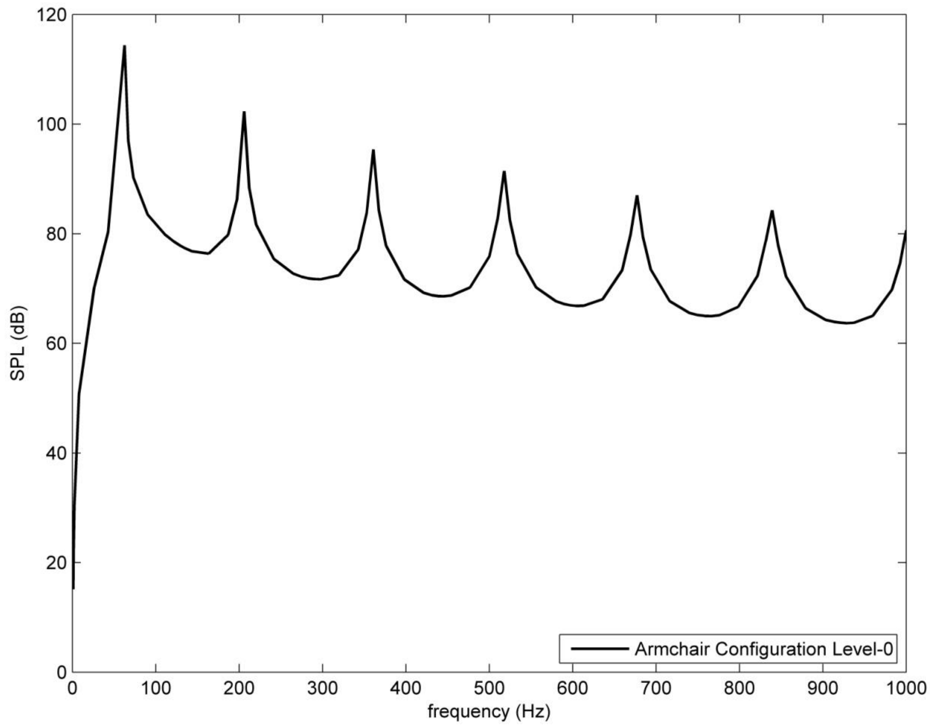


Figure 5.26 Sound pressure level of armchair configuration level-0 regular honeycomb

5.3.2 Level-1 Honeycomb

The plot shown in Figure 5.27 compares the level-0 and level-1 honeycomb structures of armchair configuration. There is a considerable reduction in the sound pressure level transmitted. Using the area under the curve measure we have found out that there is a reduction in sound pressure level by 7.04 %. Though the sound pressure level is reduced drastically, the stiffness also reduces drastically which is not a favorable trait. We observe that the number of peaks have increased from six to nine within the target frequency range.

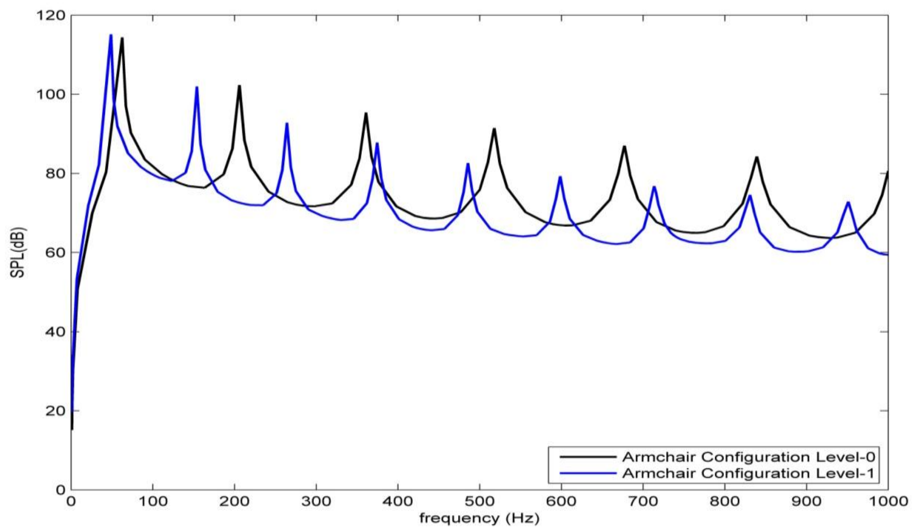


Figure 5.27: Comparison of armchair configuration level-0 and level-1 honeycomb

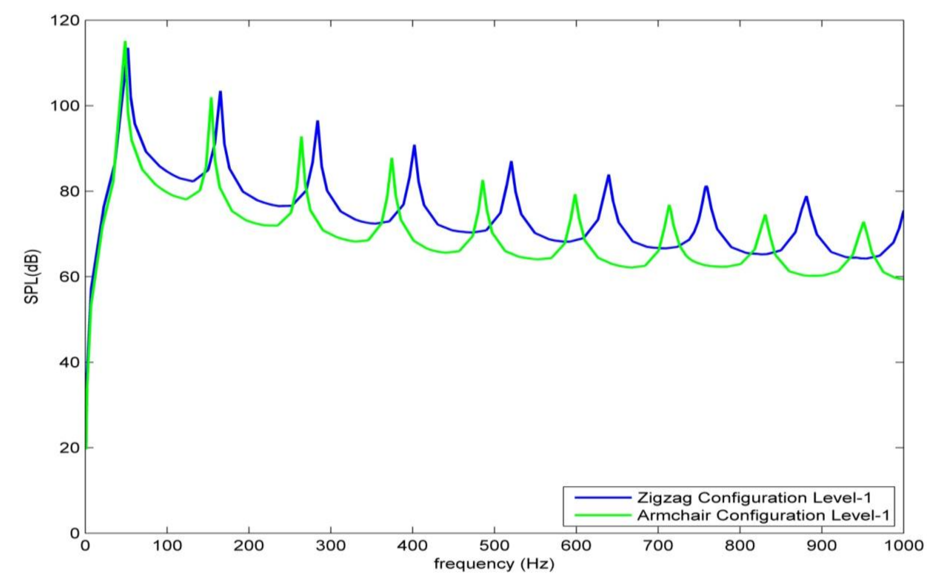


Figure 5.28: Comparison of zigzag and armchair configuration level-1 honeycomb

The plot in Figure 5.28 compares the level -1 hierarchy honeycomb for the two different configurations. We observe that zigzag configuration is much stiffer, based on

the shift of peaks for the armchair configuration structure. It was also found that the level-1 armchair configuration structure transmits less sound pressure than the level-1 zigzag configuration structure.

5.3.3 Effect of Hexagonal Corner Reinforcement

In order to study the effect of the hexagonal corner reinforcement, this comparison is done. The Figure 5.29 compares a level-0 and level-1 honeycomb structure with the hexagonal corner reinforced structure

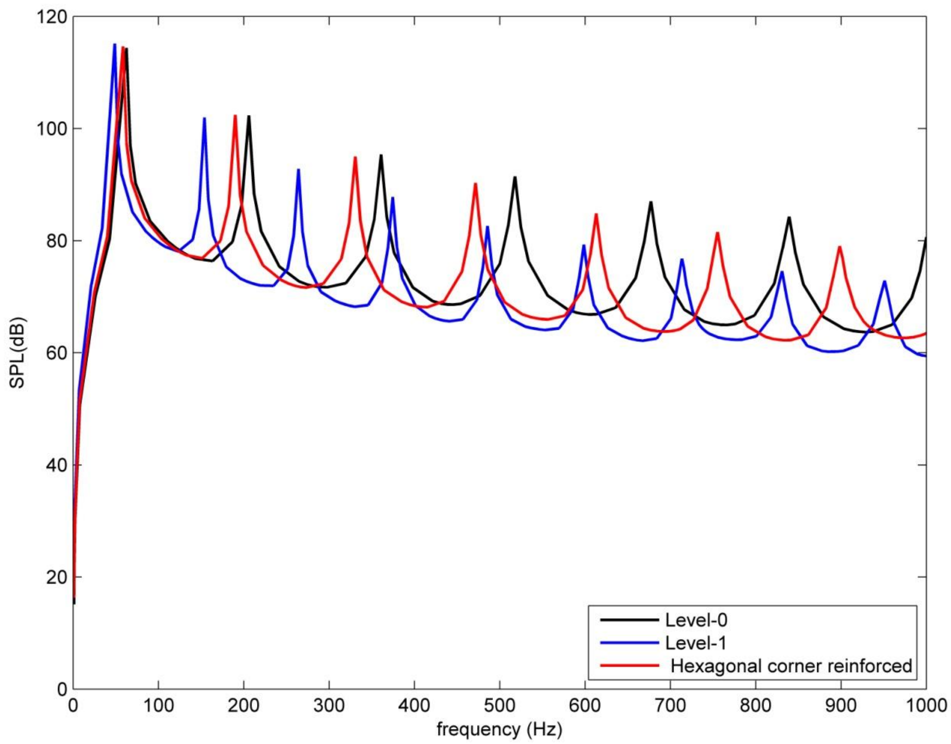


Figure 5.29: Comparison of hexagonal corner reinforced model with level-0 and level-1 honeycomb

We observe that the hexagonal reinforced structure behaves similar to level-0 than level-1 structure from Figure 5.29. Similarly the level-1* structure is compared in Figure 5.30,

with the level-1 honeycomb structure. It is stiffer and transmits more sound than the level-1 structure. And finally the level-1* and the rhombic corner reinforced structure are compared in Figure 5.31 only to find that they have almost identical sound pressure levels up to 500 Hz, after which the stiffness of the level-1*honeycomb structure starts to reduce. Thus the hexagonal corner reinforcement increases the stiffness in this case, as seen in zigzag configuration structures .The corner reinforcement does not influence the sound transmission to a very great extent

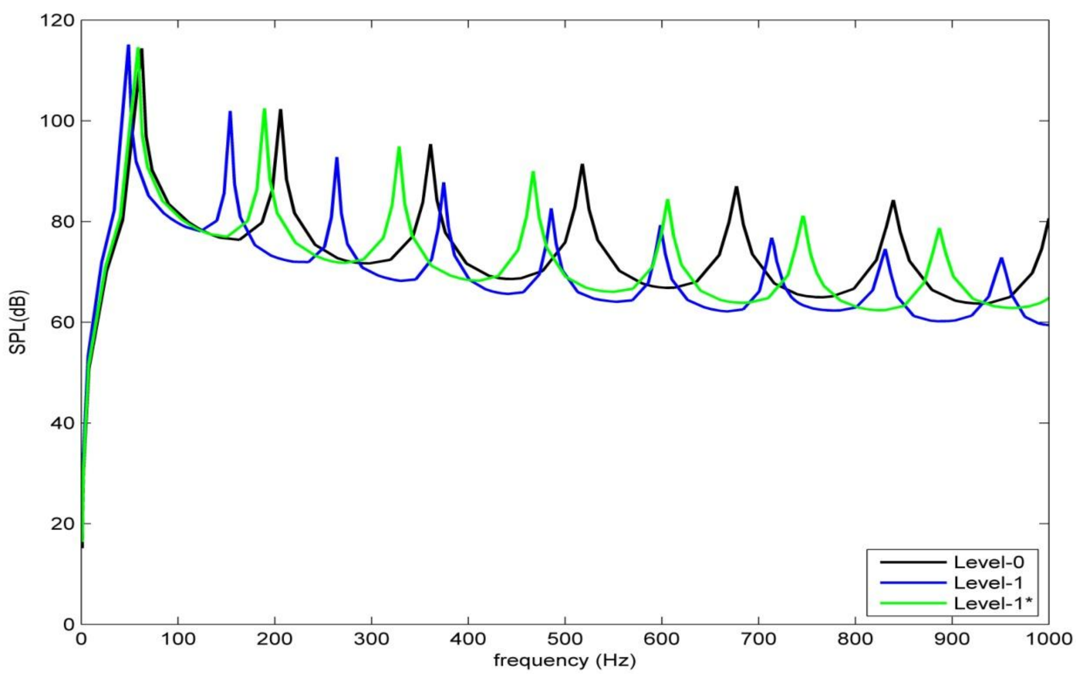


Figure 5.30: Comparison of armchair configuration level-1* structure with level-0 and level-1 honeycomb

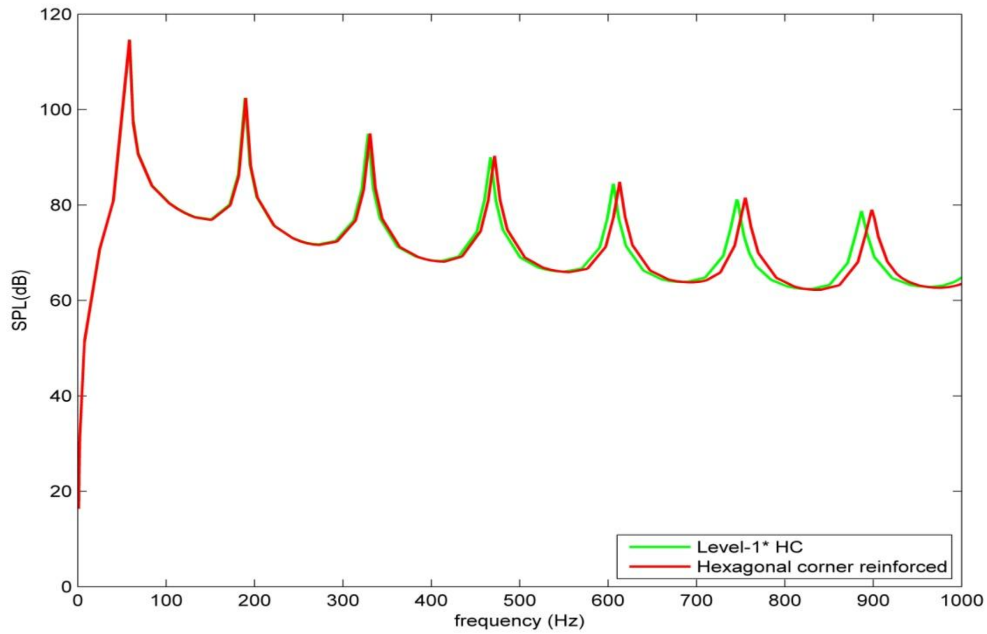


Figure 5.31: Comparison of armchair configuration level-1* structure with hexagonal corner reinforced structure.

5.3.4 Multilayered Honeycomb Structures

The study is extended to the multilayer honeycombs in order to exclude the boundary effects. Several comparison studies were performed and the results of the comparison are given in Figure 5.32, 5.33 and 5.34

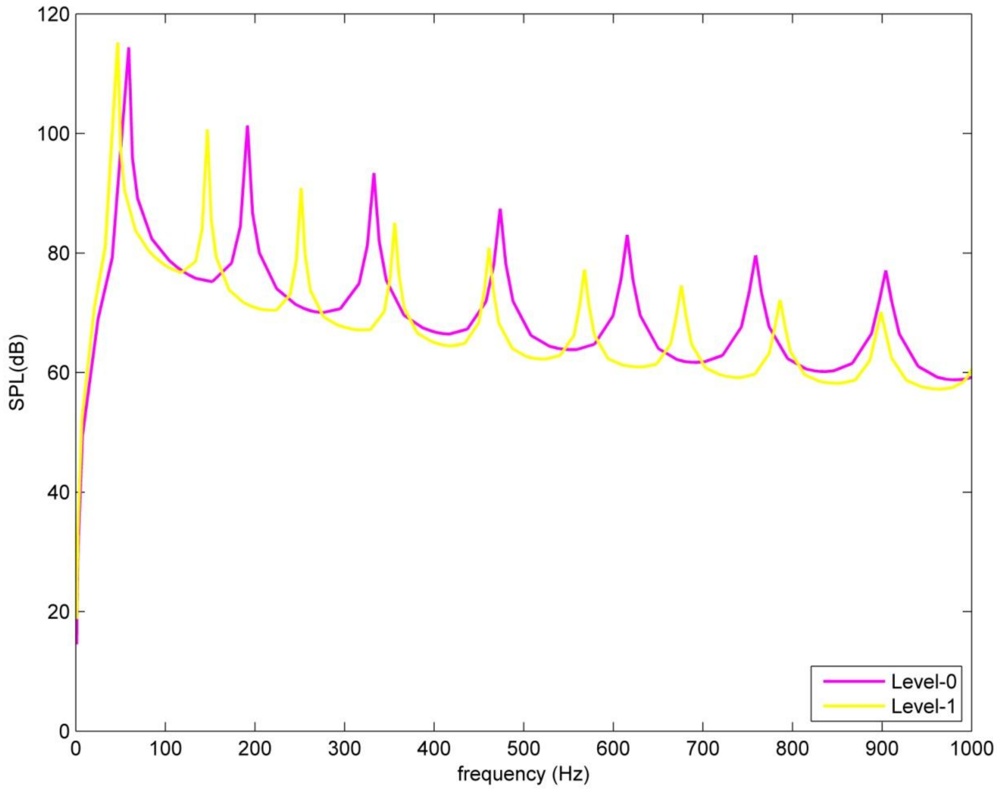


Figure 5.32: Comparison of armchair configuration multilayered level-0 and level-1 honeycomb

The plot in Figure 5.32 compares a level-0 structure with level-1 structure, both the structures being multilayered. The result further bolster the fact that level-1 honeycomb indeed transmits less sound pressure and is less stiff than the level-0 structure. Further comparisons are carried out between single and multi layer level-0 and level-1 structures. From Figures 5.33 and 5.34 it is evident that the multilayered structures are less stiff and transmit less sound than the single layered structures. One possible reason for this is the reduced thickness of the multilayered structure in order to maintain the mass constant.

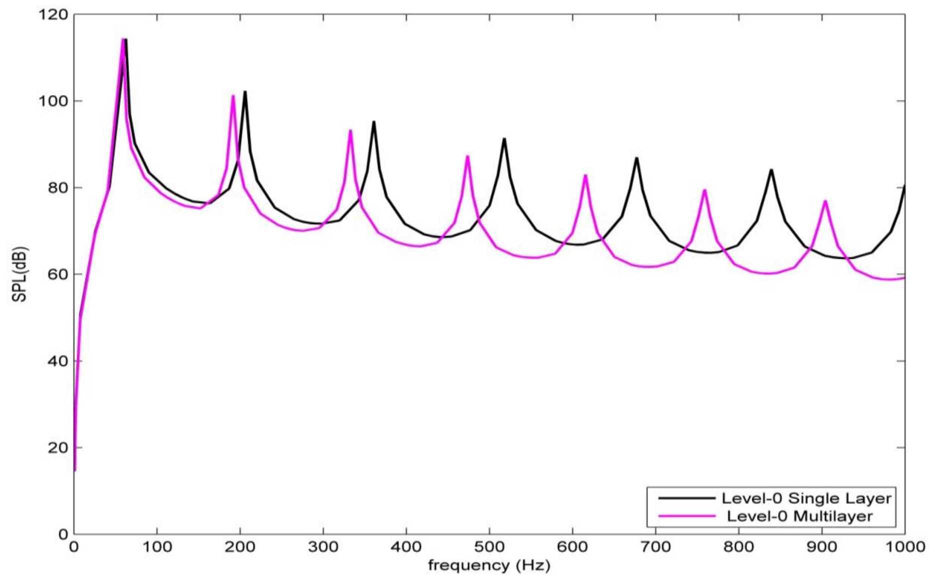


Figure 5.33: Comparison of armchair configuration multilayered level-0 and single layered level-0 honeycomb

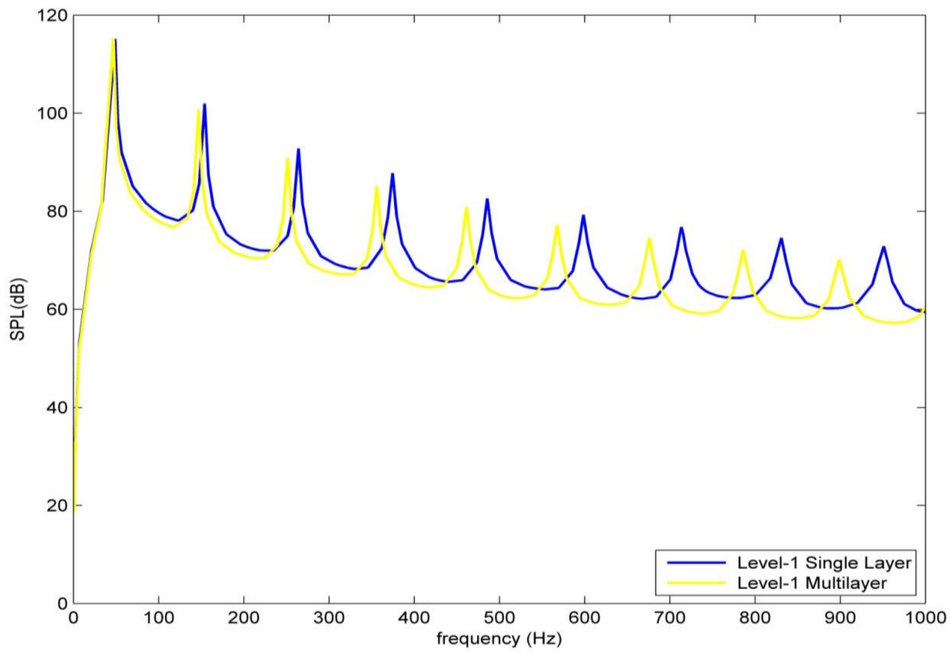


Figure 5.34: Comparison of armchair configuration multilayered level-1 and single layered level-1 honeycomb

5.3.5 Effect of Thickness Ratio between Various Levels of Hierarchy

The plot in Figure 5.35 compares the various ratios of thickness of level-1 honeycomb over the thickness of level-0 honeycombs. From this comparison we can conclude that L-0 hierarchical honeycombs are the most important factor in controlling the overall stiffness of core as doubling the thickness of level-0 cells created drastic change in stiffness. Increasing the ratio increased the stiffness and decreasing the ratio decreased the stiffness.

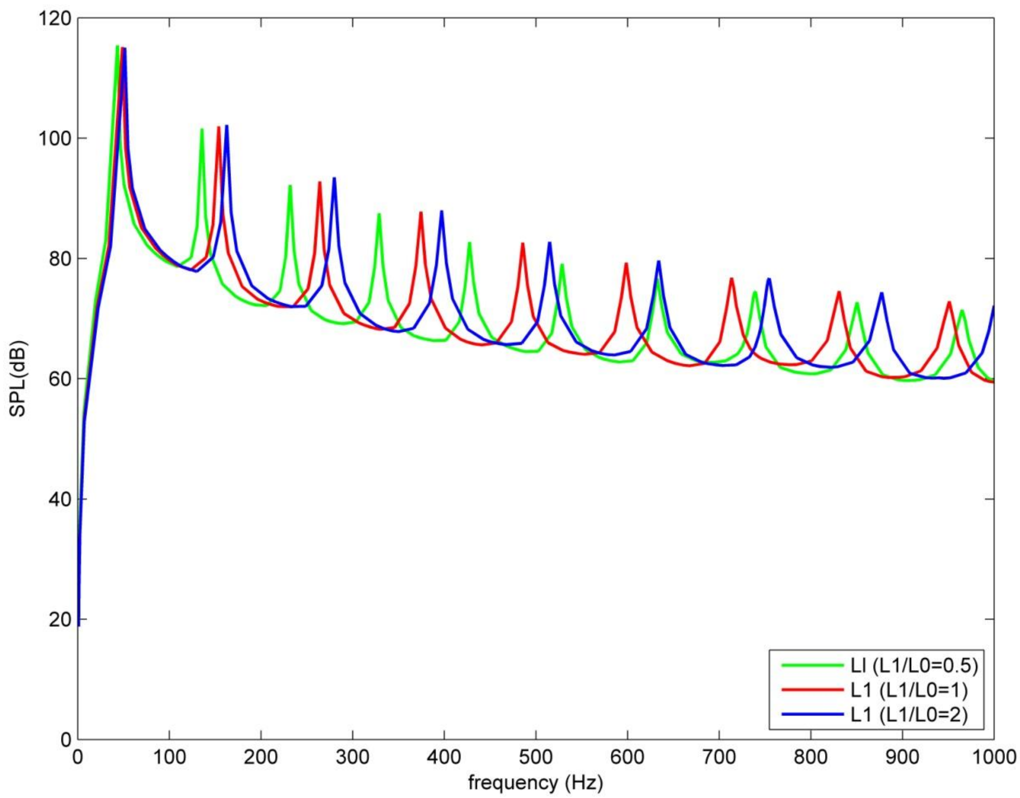


Figure 5.35: Comparison of armchair configuration level-1 honeycomb with different thickness ratio

5.3.6 Comparison of Sound Transmission for Various Honeycomb Structures

The Table 5.3 presents the value of sound pressure levels transmitted. These values are obtained by calculation the area under the curve of plots between sound pressure levels and frequency for respective structures. The Figure 5.36 is plotted using the sound pressure level values excluding the first 100 Hz.

Table 5.3: Sound pressure level of armchair configuration regular honeycomb structures

Structure	Area under the curve (dB.Hz)	Area under the curve Excluding first 100 Hz(dB.Hz)	% Decrease(Reference Value: L0 HC)
Level-0	73445.00	66390.00	
Level-1	69927.00	61711.00	7.05
Corner Reinforced	71966.00	63780.00	3.93
Level-1*	71920.00	63741.00	3.99
Multilayered L0	70005.00	61897.00	6.77
Multilayered L1	67566.00	59420.00	10.50

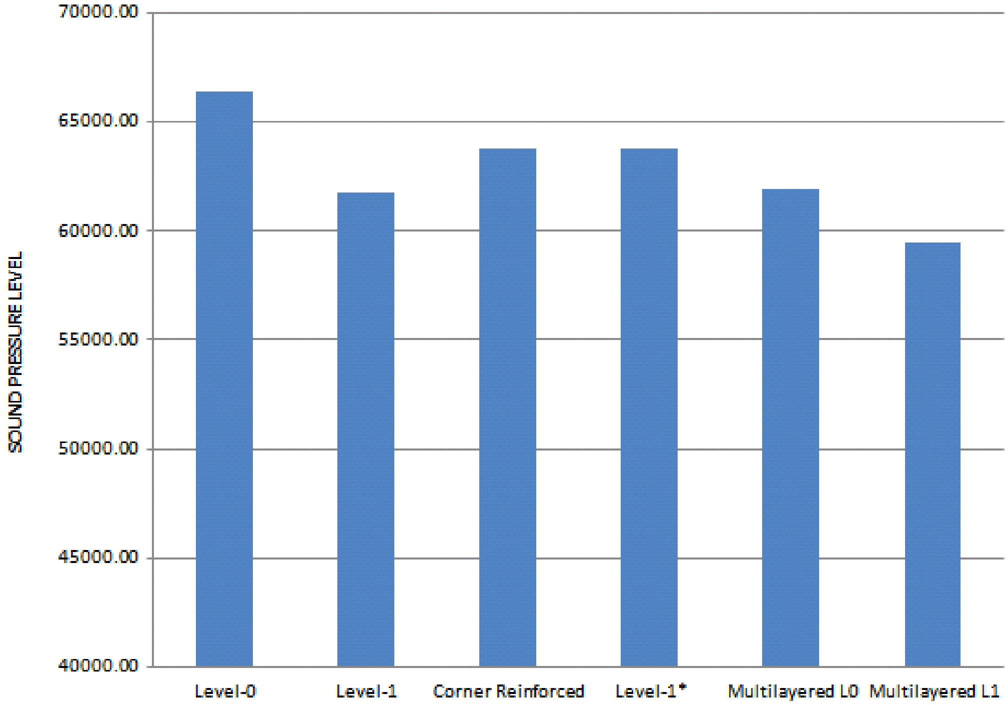


Figure 5.36: Sound pressure level of armchair configuration regular honeycomb structures

5.4 Armchair Configuration Auxetic Honeycomb Structure

In this section the results of auxetic armchair configuration structures will be discussed.

5.4.1 Level-0 Honeycomb

The level-0 honeycomb of armchair configuration is known to be one of the structures with highest sound transmission loss. But the introduction of reiterated hierarchy has further reduced the sound pressure transmitted by 1.77 %, but with a considerable loss in stiffness after 200 Hz i.e. in the resonance region. In Figure 5.37 we observe that the peaks for level-1 structure get uniform around 800 Hz; this phenomenon was also found in the zigzag configuration auxetic structure of the level-1 honeycomb.

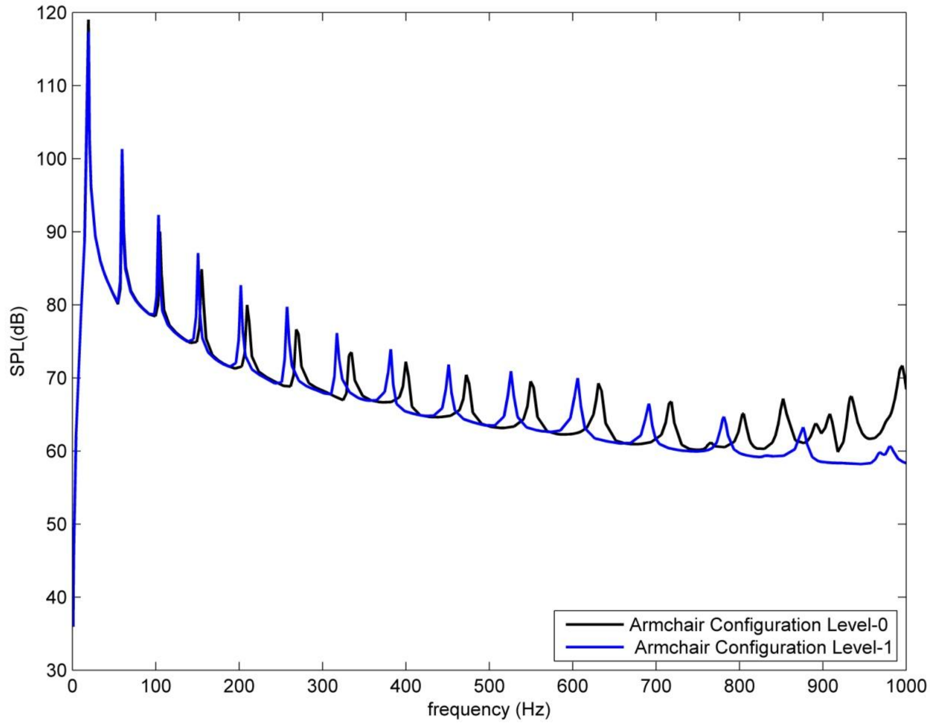


Figure 5.37: Comparison of armchair configuration auxetic level-0 and level-1 honeycomb

5.4.2 Level-1 Honeycomb

The level-1 armchair configuration structure when compared to level-1 zigzag configuration structure, it is observed that the zigzag configuration is stiffer, but transmits more sound pressure, around 11.77 % more sound pressure than the armchair configuration structure. This comparison is shown in Figure 5.38.

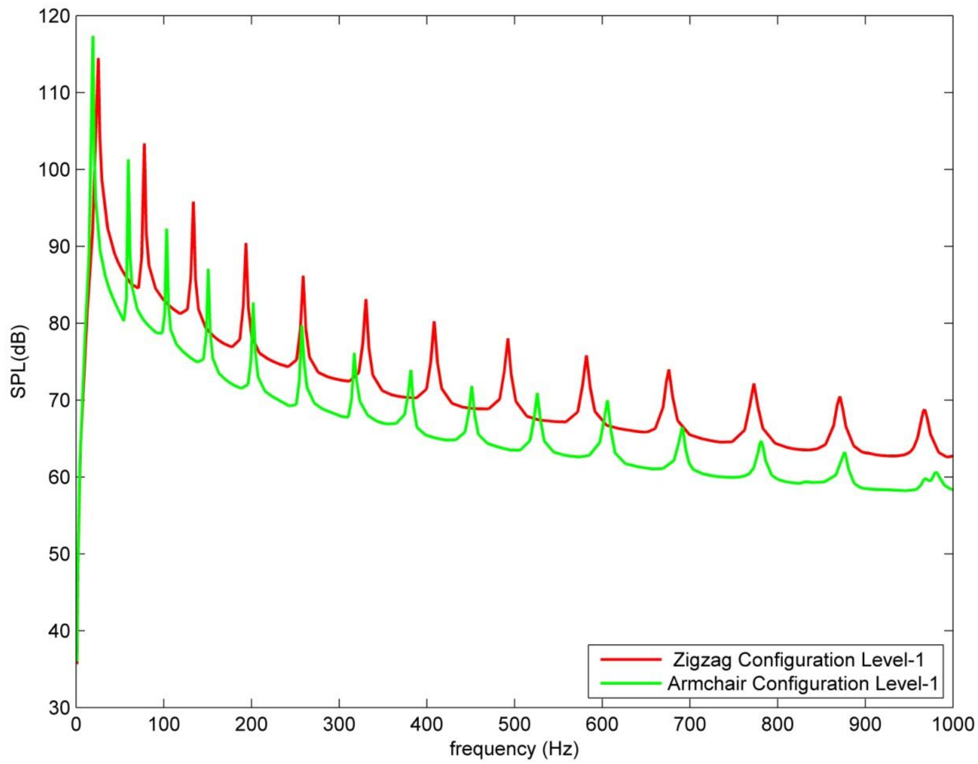


Figure 5.38: Comparison of zigzag and armchair configuration auxetic level-1 honeycomb

5.4.3 Effect of Rhombic Corner Reinforcement

Again in order to study the effect of rhombic corner reinforcement on the acoustical properties, the sound pressure levels of the rhombic corner reinforcement structure was compared with the level-1* structure in Figure 5.41. It was found that the reinforced structure had higher stiffness among the two.

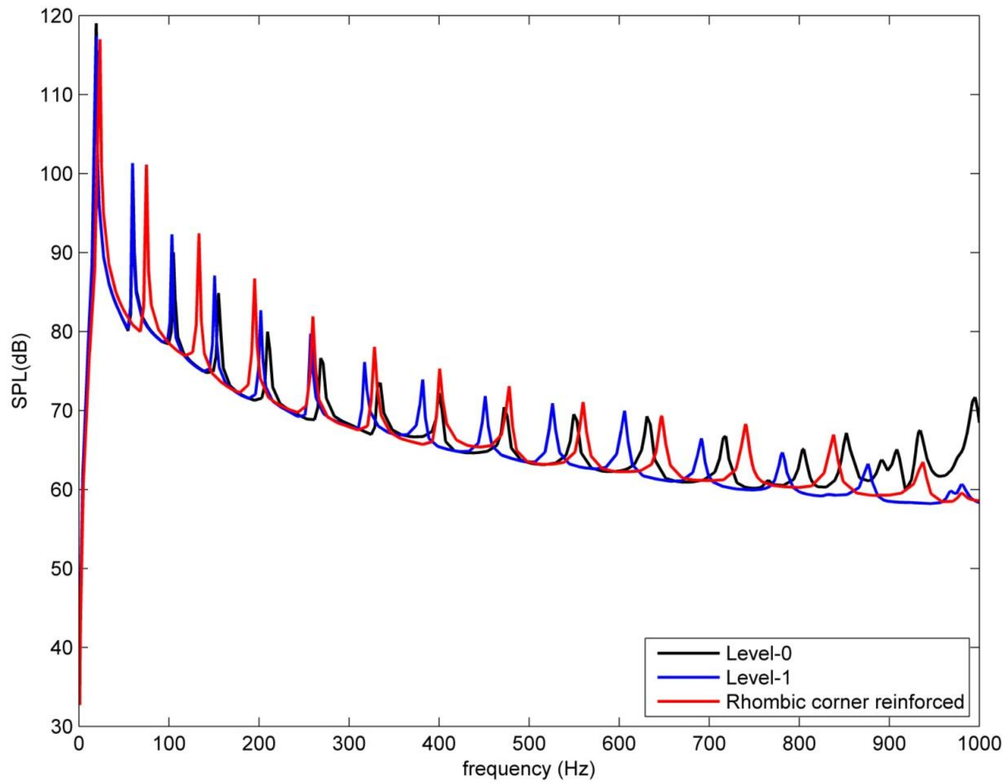


Figure 5.39: Comparison of armchair configuration rhombic corner reinforced honeycomb with auxetic level-0 and level-1 structures

From the plot in Figure 5.39, we identify that the rhombic corner reinforced structures has higher stiffness than level-0 and level-1 structures. From Figure 5.40 we observe level-1* structure reduces the stiffness drastically. The corner reinforcement play a crucial role in the increasing the stiffness of the structure. Again in this case the influence of corner reinforcement on the sound transmission is less.

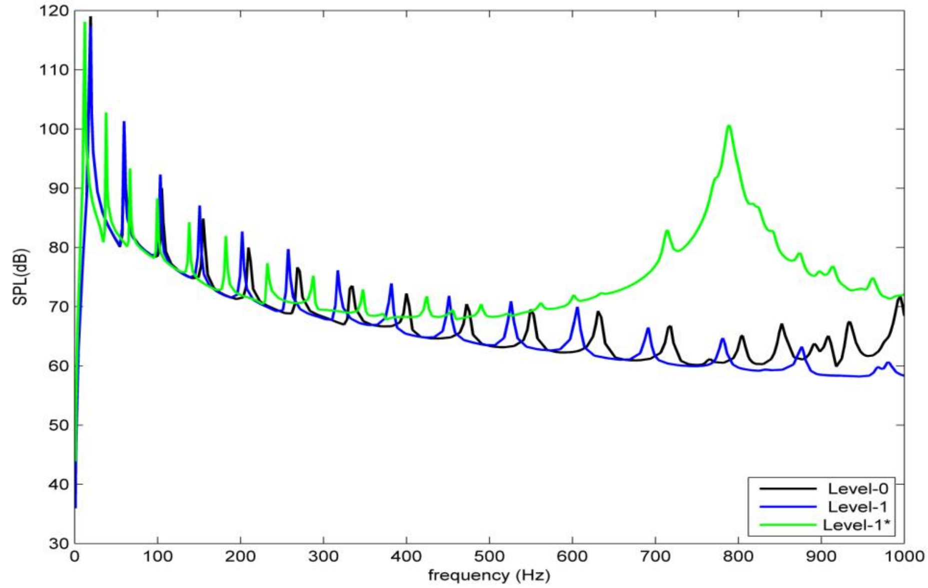


Figure 5.40: Comparison of armchair configuration auxetic level-0, level-1 and level-1* structure

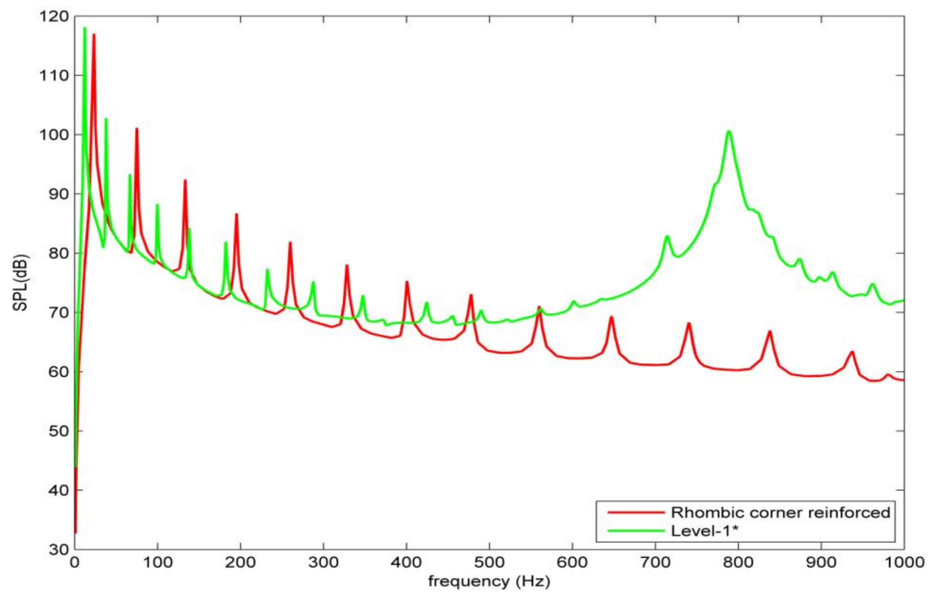


Figure 5.41: Comparison of armchair configuration auxetic rhombic corner reinforced structure and level-1* structure

5.4.4. Multilayered Honeycomb Structures

As discussed earlier the multilayered study is done to exclude the influence of boundary effects on the transmitted sound pressure levels. The first plot in Figure 5.42 compares the multilayered level-1 and level-0 honeycomb structures. We can see that there is not much difference in stiffness in the multi layered structures, as seen in the single layer structure. But the uniformity of the peaks at the higher frequencies, which was found in the single layer level-1 structure, was not present in the multilayered structure. While comparing single and multilayered structures both the level-0 and level-1 structures transmits less sound pressure than their corresponding single layer structure, which is seen in Figure 5.43and 5.44.

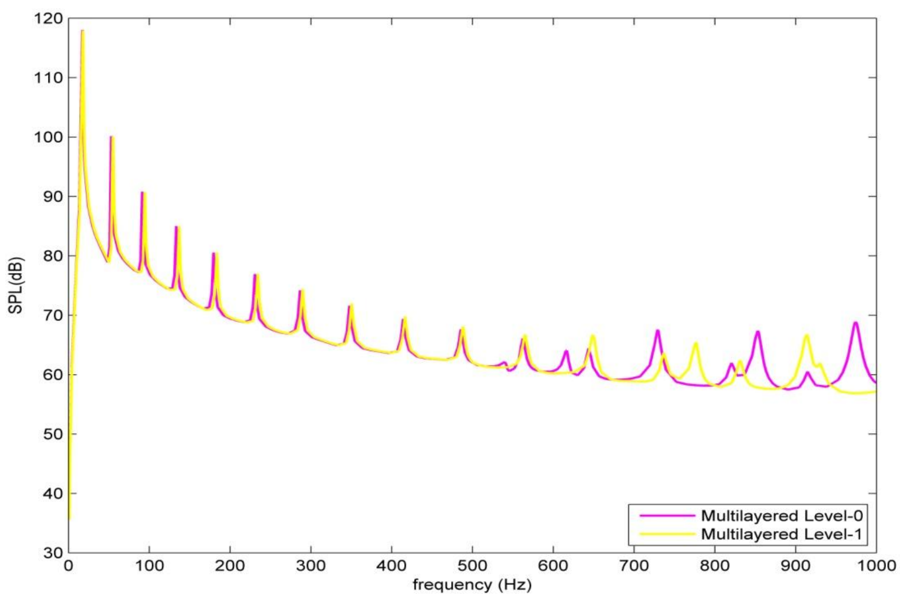


Figure 5.42: Comparison of armchair configuration multilayered auxetic level-0 and level-honeycomb

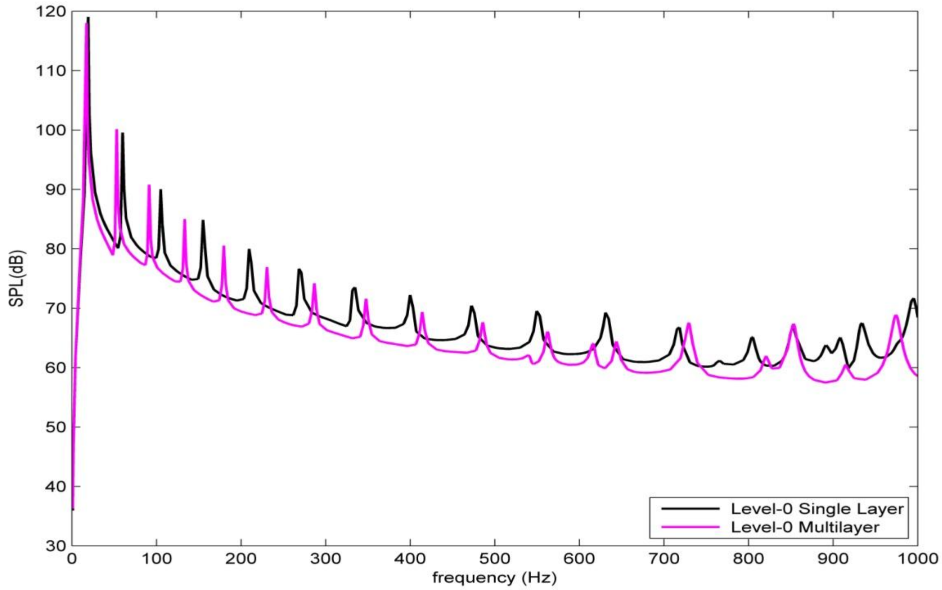


Figure 5.43: Comparison of armchair configuration single layered and multilayered level-0 structures

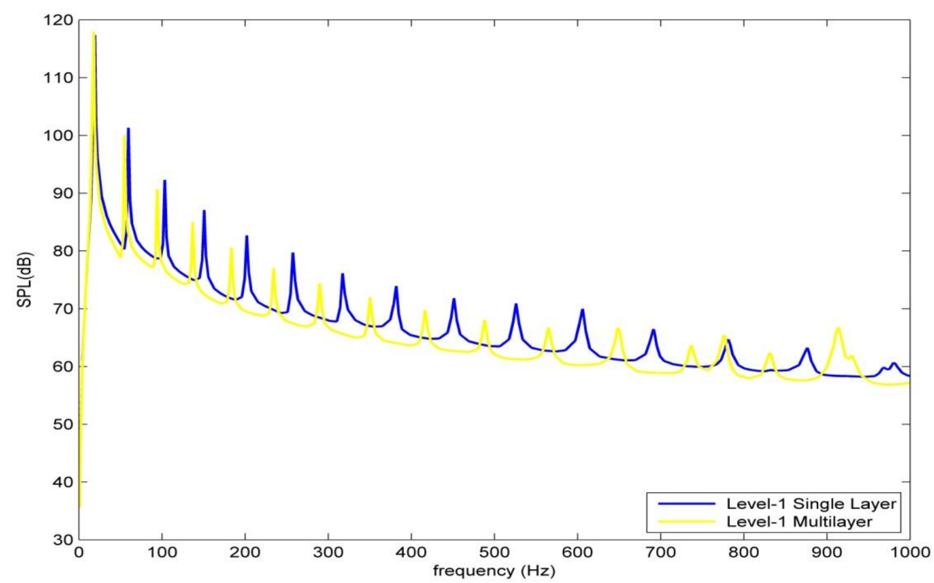


Figure 5.44: Comparison of armchair configuration single layered and multilayered level-01structures

5.4.5 Effect of Thickness Ratio of Various Levels of Hierarchy

As discussed earlier the thickness effect of the honeycombs belonging to various levels of hierarchy are done by varying the thickness of honeycombs belonging to level-1 structure separately and level-0 structure separately. From the Figure 5.45 we see that there is not much difference in stiffness between the ratio-1 structure and ratio-2 structure up to 250 Hz, beyond which ratio-2 structure i.e. the structure with thickness of level-1 honeycombs twice thicker than the level-0 honeycombs, has stiffness being gradually reduced. Unlike the case of regular honeycombs, the ratio-1 structure is the stiffest structure. Therefore reducing the ratio reduced the stiffness of the structure but increasing the ratio does not increase the stiffness of the structure.

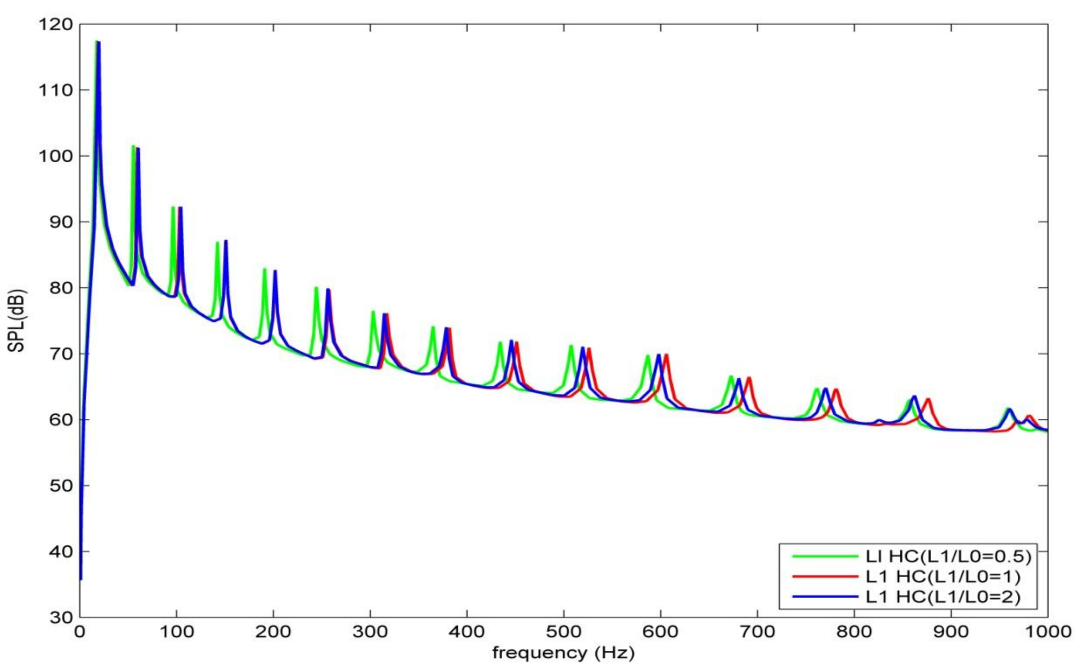


Figure 5.45: Comparison of armchair configuration level-1 honeycomb with different thickness ratio

5.4.6 Comparison of Sound Transmission for Various Auxetic Honeycomb Structures

The Table 5.4 provides the sound pressure levels transmitted by various auxetic structures of armchair configuration. The sound pressure levels are expressed in terms of area under the curve of respective plots between sound pressure levels and frequency .The sound pressure level plotted in Figure 5.46 is created using the sound pressure level excluding the first 100 Hz.

Table 5.4: Sound pressure level of armchair configuration auxetic honeycomb structures

Structure	Area under the curve (dB.Hz)	Area under the curve Excluding first 100 Hz(dB.Hz)	% Decrease(Reference Value: L0 HC)
Level-0	67779	59558	
Level-1	66813	58505	1.77
Corner Reinforced	67335	59057	0.84
Level-1*	75024	61794	-3.75
Multilayered L0	65493	57319	3.58
Multilayered L1	65302	56873	4.51

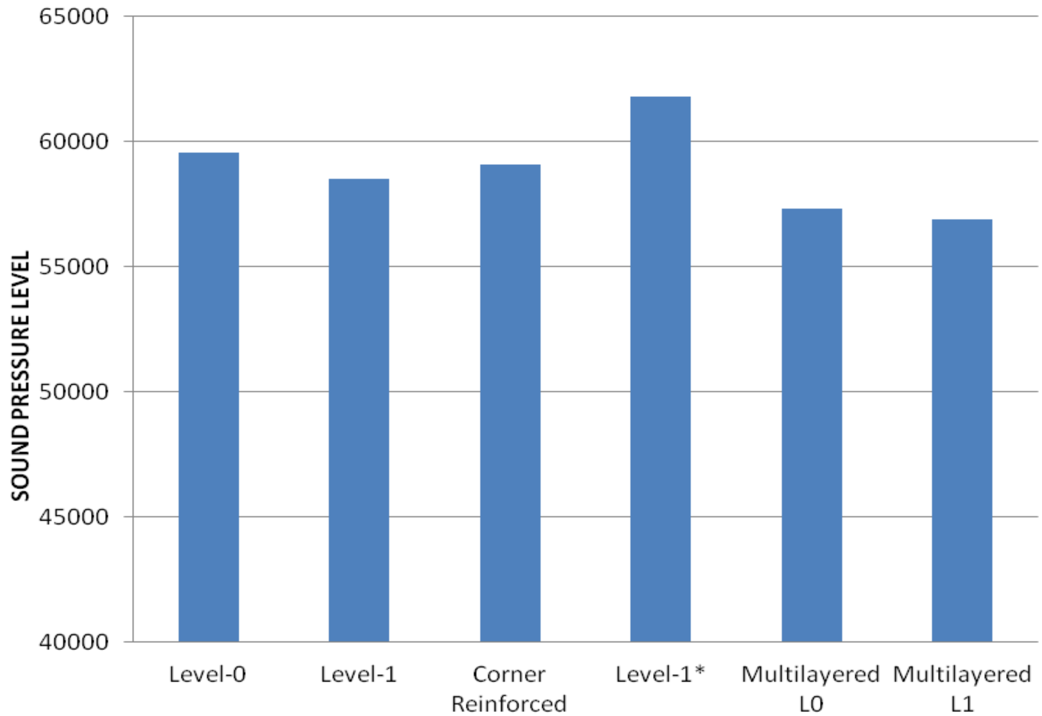


Figure 5.46: Sound pressure level of armchair configuration auxetic honeycomb structures

5.5 Case Study with Reduced Face Plate Thickness

Level-0 and level-1 regular structures of zigzag configuration and level-0 and level-1 auxetic structures of armchair configuration were studied by reducing the thickness of face sheet .The face sheet thickness was reduced from .0025m to.001m The mass of entire panel was maintained constant as in the previous studies. In order to maintain the mass constant the thickness of the core had to be increased.

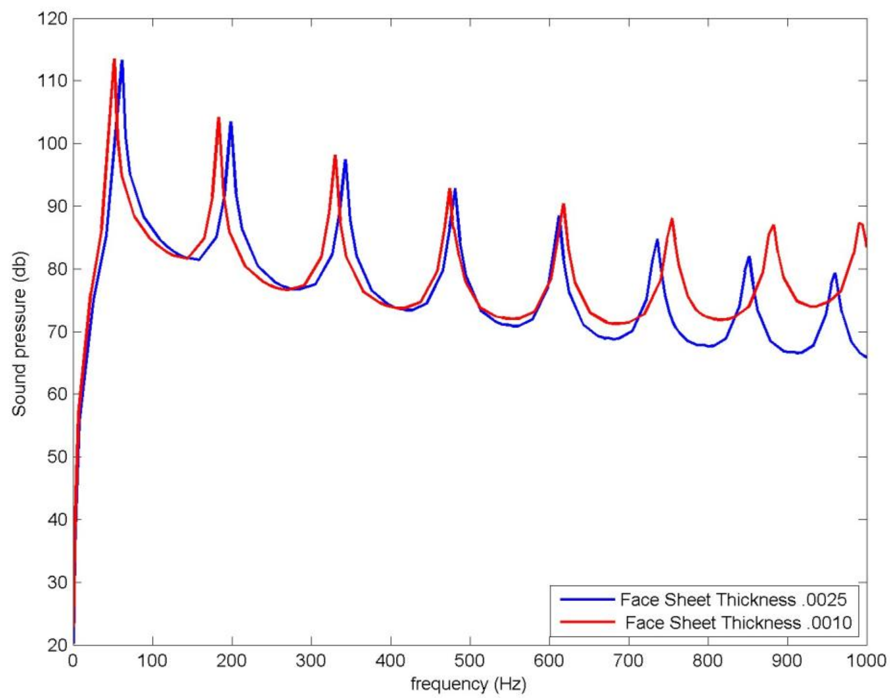


Figure 5.47 Comparison of zigzag configuration regular honeycomb structures with face sheet thickness.0025m and .0010m.

From Figure 5.47 we can observe that the reducing the thickness of face sheet of zigzag configuration regular honeycomb reduced the stiffness initially up to 600 Hz , after which the structure becomes stiffer and also transmits more sound, due to the increased stiffness.

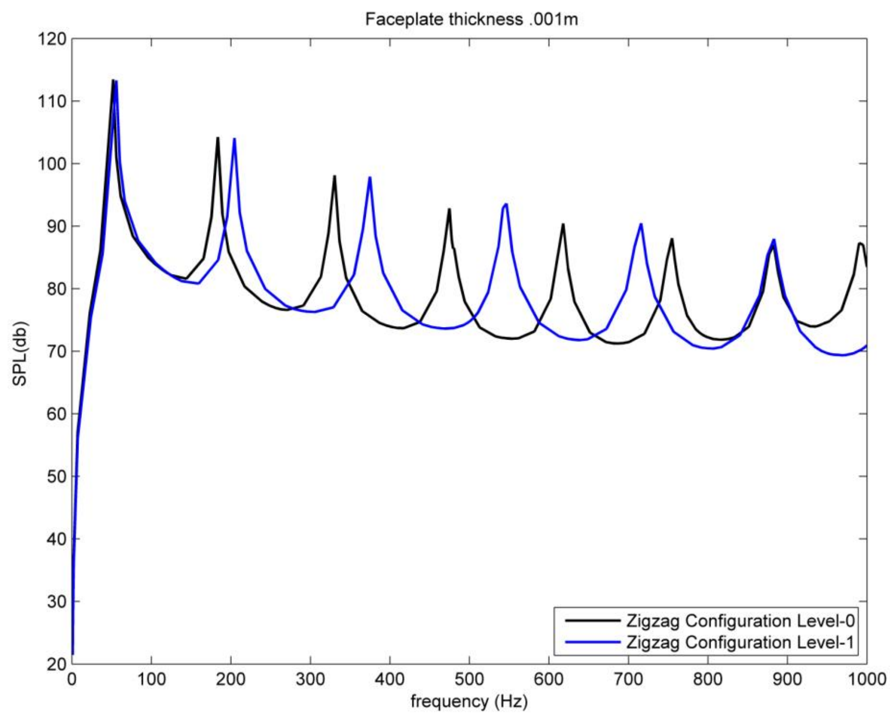


Figure 5.48 Comparison of zigzag configuration regular honeycomb level-0 and level-1 structures with face sheet thickness.0010m.

In this comparison both level-0 and level-1 regular structures have constant mass of 73.96 kg but with face sheet thickness of .001m. We can see a completely different behavior as the inclusion of level-1 hierarchy structures has created a increase in the stiffness of the structure and also increase in sound transmission. Hence we can conclude that the thickness of face plate plays an important role in controlling the behavior of sandwich panel. It also indirectly means the thickness of the core plays an important role in deciding the stiffness of constant mass panel.

A similar study was conducted using armchair configuration auxetic level-0 and level-1 structures.

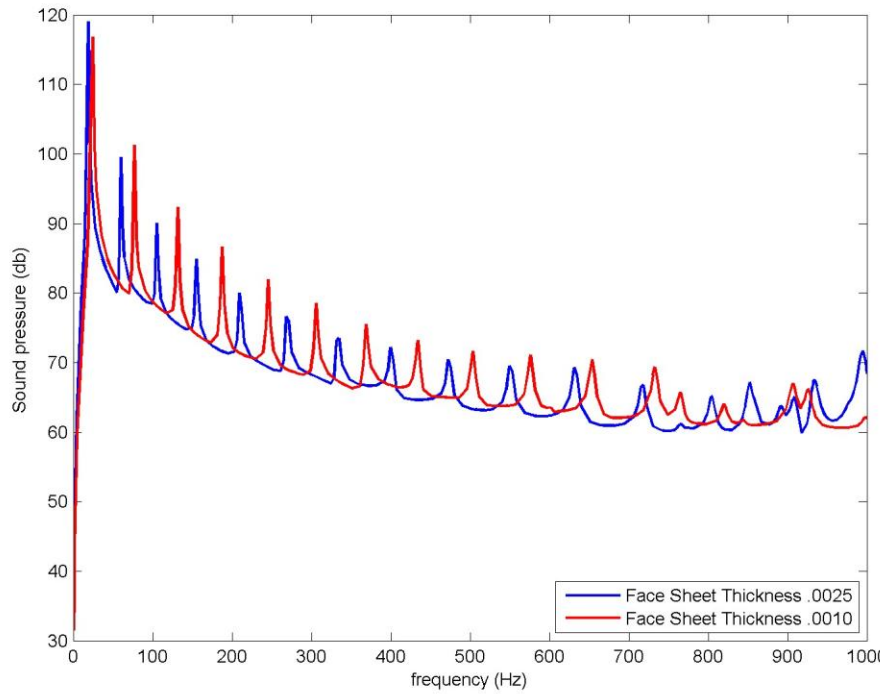


Figure 5.49 Comparison of armchair configuration auxetic honeycomb structures with face sheet thickness.0025m and .0010m.

In the case of auxetic armchair structures reducing the face sheet thickness, increases the stiffness of the structure and transmits higher sound pressure levels as shown in Figure 5.47. When this structure was compared with a level-1 structure with face sheet thickness of .001m in Figure 5.50, we found that there an increase in stiffness and sound pressure levels. This can be due to core contributing more stiffness to the structure and mode shapes being dominated by the core of the panel rather than the face sheet.

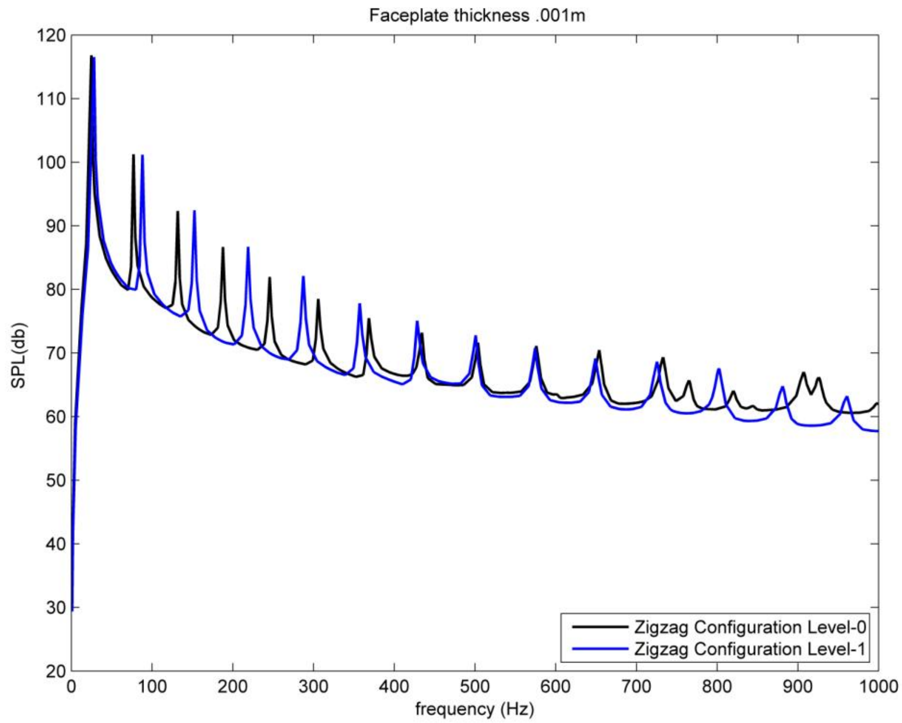


Figure 5.50 Comparison of zigzag configuration regular honeycomb level-0 and level-1 structures with face sheet thickness.0010m

CHAPTER-6

CONCLUSION AND FUTURE WORK

This study primarily used two configurations of honeycomb structures namely the zigzag configuration and the armchair configuration and introduced hierarchy in the honeycomb structure to study the influence of reiterated hierarchy on the sound transmission characteristics. Along with this the influence of corner reinforcement on the sound transmission property and the effect on thickness ratio between various levels of hierarchy were also studied. From this work, several conclusions can be drawn.

Based on the results from the natural frequency extraction procedure, we can conclude that the stiffness of all structures belonging to a particular configuration was in the same range except for the level-1* for auxetic structures and corner reinforced models for regular structures. The level-1* auxetic structure exhibited reduced stiffness irrespective of the configuration. The level-1 * regular structures were the stiffest irrespective of the configuration. For regular structures, irrespective of configuration the stiffness of single layered structures was closer to their respective multilayered structures. There was no particular trend observed for single and multilayered auxetic structures.

Another important observation was the rate of change of natural frequency increase around 700-750 Hz for most of the models and when the mode shapes were inspected the first dilatational mode shape appeared around 700-750 Hz. While comparing the static and dynamic stiffness of single and multilayered structures, all but

multilayered level-0 regular structure of zigzag configuration behaved unpredictably. Rest of the structures had similar stiffness behavior in both static and dynamic conditions.

Analyzing the sound pressure levels of various structures, revealed that multilayered structures transmitted less sound compared to single layer structures with the only exception being multilayered level-1 auxetic structure. Among the regular honeycomb structures the armchair configuration transmitted less sound than the zigzag configuration with the exception of multilayer zigzag configuration. The auxetic structures with armchair configuration were transmitting less sound pressure than their respective zigzag configuration with one exception of multilayered zigzag configuration. A general trend observed was that auxetic honeycomb structures transmitted less sound with respect to regular honeycombs of both zigzag and armchair orientation. The most important observation is that the introduction of reiterated honeycomb structures resulted in reduction of sound transmission varying from 1-7%.

Studying the comparison between corner reinforced structures, level-1 and level-1* showed that the corner reinforcement does not influence the sound transmission as much as the influence of level-0 links in the honeycomb. The level-1* models increase the sound transmission level and bring it close to the sound transmitted by level-0 structure. And also the corner reinforced structures increased the stiffness of armchair configuration structures but reduced the stiffness of zigzag configuration honeycomb structures.

The ratio of thickness between level-1 and level-0 honeycomb does not influence the sound transmission property to a very great extent. This trend has been consistent

with all the structures. Increasing the ratio resulted in increasing the stiffness in regular honeycombs, but resulted in decreasing the stiffness for auxetic honeycombs. Decreasing the ratio decreased the stiffness for regular honeycombs and auxetic honeycomb of armchair configuration but did not have a pronounced effect on the auxetic honeycomb in zigzag configuration.

For the special case with reduced face sheet thickness, but constant mass of 73.96 kg it as found that there is an increase in the transmitted sound pressure levels and increase in the stiffness of the structure. An important observation was reducing the face sheet thickness, resulted in increase of core thickness as the mass had to be maintained constant, which can be actual reason for increase in stiffness. Therefore the redistribution of mass from the face plate to the core increased the stiffness of the structure but also increased the transmitted sound pressure level. Under static conditions reducing the face sheet thickness by 60 % reduced the stiffness of the structure on an average by 60.14 %.

6.1 Future Work

The present work was primarily concerned with sound transmission properties in the 0-1000 Hz frequency range. In the future, this work can be extended up to 2000 Hz or 10 kHz. Also the number of layers of honeycomb can be further increased and its effect on the sound transmission can be studied. Also other possible orientation and core geometries with reiterated hierarchy could be studied. Some possible structures are presented in Figure 1.1 and Figure 1.2. Also further studies can be carried using various face sheet thickness.

The use of alternate material in different levels of hierarchy has also not been studied so far and can be taken up in the future. The corner reinforcement can also be made of different material with better sound absorption properties. This configuration could have both high structural strength and better sound reduction properties.

APPENDICES

Appendix A

Natural Frequency of All Structures

Table A1: All natural frequency of zigzag orientation regular honeycomb models

Mode #	Level-0	Level-1	Level-2	Hexagonal corner reinforced	Level-1*	Multi layer L-0	Multi layer L-1
1	61.703	52.137	50.942	59.751	59.457	63.14	51.343
2	126.26	105.41	102.82	121.28	120.88	130.06	104
3	199.13	165.07	160.84	190	190.71	205.7	162.65
4	271.68	224.45	218.59	257.07	260.76	281.41	220.96
5	343.29	283.88	276.43	321.61	330.64	356.54	279.31
6	413.18	343.02	334.08	382.67	399.7	430.38	337.43
7	481.44	402.17	391.82	440.23	468.16	503.07	395.58
8	547.87	461.31	449.65	494.11	535.91	574.46	453.78
9	612.48	520.57	507.72	544.42	603.04	644.56	512.14
10	675.19	579.96	566.04	591.25	669.49	713.27	570.7
11	736	639.59	624.73	634.81	735.24	758.51	629.53
12	755.58	699.45	683.81	675.29	754.47	780.57	688.67
13	794.87	748.68	743.36	712.92	800.34	846.36	743.46
14	851.86	759.65	746.56	747.84	864.7	910.61	748.19
15	906.98	820.19	803.41	758.52	928.27	973.25	808.12
16	960.31	881.16	864.06	780.16	991.09		868.53
17		942.59	925.33	809.73			929.46
18			987.3	836.4			990.98
19				859.69			
20				878.97			
21				893.46			
22				902.66			
23				907.18			
24				911.37			
25				921.08			
26				939.6			
27				967.86			

Table A2: All natural frequency of zigzag orientation auxetic honeycomb models

S.NO	Level-0	Level-1	Rhombic corner reinforced	Level-1*	Multi layer L-0	Multi layer L-1
1	27.593	25.343	30.882	18.91	23.365	23.524
2	55.178	50.854	61.716	37.797	46.678	47.13
3	84.171	77.883	94.404	57.537	71.07	71.996
4	112.98	105.35	126.75	77.494	95.453	97.145
5	141.95	133.71	159.13	97.932	120.13	122.93
6	171.05	163.08	191.48	118.92	145.1	149.4
7	200.37	193.68	223.89	140.6	170.49	176.68
8	229.94	225.63	256.38	163.05	196.34	204.82
9	259.81	259.05	288.97	186.37	222.74	233.87
10	290.01	294	321.69	210.63	249.71	263.87
11	320.54	330.54	354.55	235.91	277.32	294.85
12	351.43	368.68	387.58	262.26	305.6	326.81
13	382.67	408.41	420.78	289.76	334.59	359.77
14	414.27	449.68	454.18	318.44	364.29	393.74
15	446.16	492.43	487.76	348.34	394.73	428.72
16	478.34	536.56	521.57	379.49	425.88	464.71
17	510.68	581.94	555.54	411.92	457.73	501.7
18	543.14	628.48	589.75	445.63	490.2	539.67
19	575.45	645.45	624.03	480.64	523.21	578.59
20	607.65	676	658.59	516.92	556.6	618.41
21	614.45	724.19	692.47	534.23	590.12	625.58
22	639.45	772.99	705.38	554.47	623.36	659.03
23	669.99	821.92	727.7	593.24	643.35	700.3
24	699.58	838.51	762.35	619.99	655.65	741.91
25	726.53	871.06	796.31	633.17	685.81	783.24
26	738.25	902.66	830.2	650.37	711.79	796.25
27	751.77	919.8	863.07	674.18	730.23	822.76
28	765.94	951.71	895.31	677.37	846.63	856.07
29	773.27	967.77	925.7	707.02	911.07	863.04
30	783.59	999.51	954.9	716.24	930.8	921.5
31	790.49		979.35	740.36	948.31	981.87
32	799.15		993	759.13	955.6	991.23
33	804.04			777.13	974.09	1000.5
34	811.99			802.7	998.25	

35	814.34			816.85		
36	820.32			846.67		
37	820.92			858.8		
38	941.31			890.57		
39	941.33			901.84		
40				935.88		
41				944.77		
42				947.51		
43				980.36		
44				994.14		

Table A3: All natural frequency of armchair orientation regular honeycomb models

Mode #	Level-0	Level-1	Hexagonal corner reinforced	Level-1 *	Multi layer L-0	Multi layer L-1
1	62.62	48.896	58.568	58.817	59.214	46.899
2	129.77	98.617	120.4	120.04	121.41	94.311
3	205.99	153.96	190.13	189.3	191.63	146.93
4	283.13	208.99	260.24	258.78	262.09	199.16
5	360.96	264.16	330.7	328.41	332.74	251.5
6	439.09	319.23	401.09	397.74	403.19	303.71
7	517.83	374.49	471.63	467.1	473.77	356.06
8	597.14	429.94	542.27	536.45	544.5	408.55
9	677.14	485.74	613.09	605.99	615.54	461.32
10	757.8	541.92	684.09	675.7	686.95	514.37
11	759.8	598.56	699.85	745.71	758.82	567.8
12	839.15	655.71	755.3	754.76	759.15	621.63
13	921.16	713.43	826.71	816	831.18	675.94
14		739.41	898.31	886.66	904.1	730.75
15		771.78	933.78	957.68	977.62	731.08
16		830.8	970.59			786.14
17		890.54				842.12
18		951.05				898.77
19						956.13

Table A4: All natural frequency of armchair orientation auxetic honeycomb models

S.NO	Level-0	Level-1	Rhombic corner reinforcement	Level-1*	Multi layer L-0	Multi layer L-1
1	19.354	19.322	23.344	12.28	17.268	17.951
2	39.064	38.888	47.795	24.795	34.686	36.026
3	60.188	59.649	75.055	37.976	52.951	54.956
4	82.262	81.07	103.61	51.86	71.738	74.33
5	105.55	103.39	133.33	66.69	91.319	94.406
6	130.01	126.61	163.82	82.614	111.79	115.26
7	155.66	150.78	195.09	99.773	133.28	137
8	182.45	175.9	227.08	118.26	155.85	159.7
9	210.36	202.03	259.9	138.14	179.57	183.44
10	239.37	229.17	293.56	159.47	204.48	208.26
11	269.49	257.39	328.23	182.26	230.62	234.23
12	300.71	286.71	363.88	206.51	257.99	261.38
13	333.07	317.19	400.68	232.21	286.64	289.78
14	366.56	348.85	438.59	259.31	316.55	319.46
15	401.2	381.73	477.8	287.73	347.76	350.44
16	436.99	415.85	518.17	317.3	380.27	382.77
17	473.94	451.26	559.97	347.56	414.07	416.47
18	512.02	487.96	602.9	351.6	449.17	451.55
19	551.2	525.98	645.05	373.75	485.56	488.04
20	591.41	563.85	647.45	376.49	487.51	495.46
21	604.2	565.3	692.62	395.44	523.24	525.94
22	632.66	605.95	740.26	405.49	541.65	562.38
23	674.76	647.89	750.19	407.11	562.19	565.28
24	717.57	691.16	790.36	424.45	572.4	600.44
25	747.15	695.52	838.02	455.42	602.39	606.03
26	760.97	735.63	890.04	456.62	616.76	648.21
27	764.45	764.06	890.33	489.92	643.8	650.8
28	804.78	781.43	937.5	500.73	669.84	691.8
29	817.02	805.09	979.64	523.45	686.39	710.52
30	848.77	828.69	994.34	525.72	728.83	736.8
31	852.37	830.52		549.94	730.12	776.37
32	888.4	876.32		562.15	774.9	783.16
33	892.4	898.67		598.7	790.54	830.89
34	909.56	925.5		601.82	820.68	844.73

35	933.15	966.54		634.79	853.1	879.6
36	935.22	969.11		661.24	860.56	885.23
37	954.83	980.23		669.61	867.45	913.63
38	976.69			701.87	914.65	930.23
39	985.63			714.23	914.77	981.06
40	994.83			729.42	962.8	981.78
41				749.27	974.24	
42				751.34	983.34	
43				756.54		
44				757.12		
45				758.08		
46				759.24		
47				760.14		
48				760.85		
49				762.56		
50				763.76		
51				764.61		
52				765.01		
53				772.42		
54				785.63		
55				788.45		
56				789.46		
57				791.36		
58				794.45		
59				796.3		
60				799.47		
61				806.55		
62				808.13		
63				817.42		
64				822.35		
65				822.52		
66				824.43		
67				829.39		
68				830.38		
69				831.76		
70				837.47		
71				837.57		
72				842.8		

73				844.31		
74				849.75		
75				854.13		
76				854.32		
77				858.06		
78				858.44		
79				866.85		
80				867.62		
81				872.04		
82				874.58		
83				876.38		
84				883.7		
85				893.12		
86				893.41		
87				893.99		
88				897.11		
89				902.8		
90				910.63		
91				914.31		
92				914.73		
93				916.78		
94				921.24		
95				926.67		
96				931.11		
97				931.17		
98				937.01		
99				939.67		
100				941.02		
101				943.15		
102				945.2		
103				946.48		
104				950.73		
105				953.74		
106				956.78		
107				960.02		
108				962.32		
109				965.55		
110				967.13		

111				968.25		
112				970.81		
113				972.87		
114				974.53		
115				975.71		
116				977.52		
117				978.14		
118				980.65		
119				986.4		
120				989.67		

Appendix B

Comparison of Sound Pressure Levels of All Structures

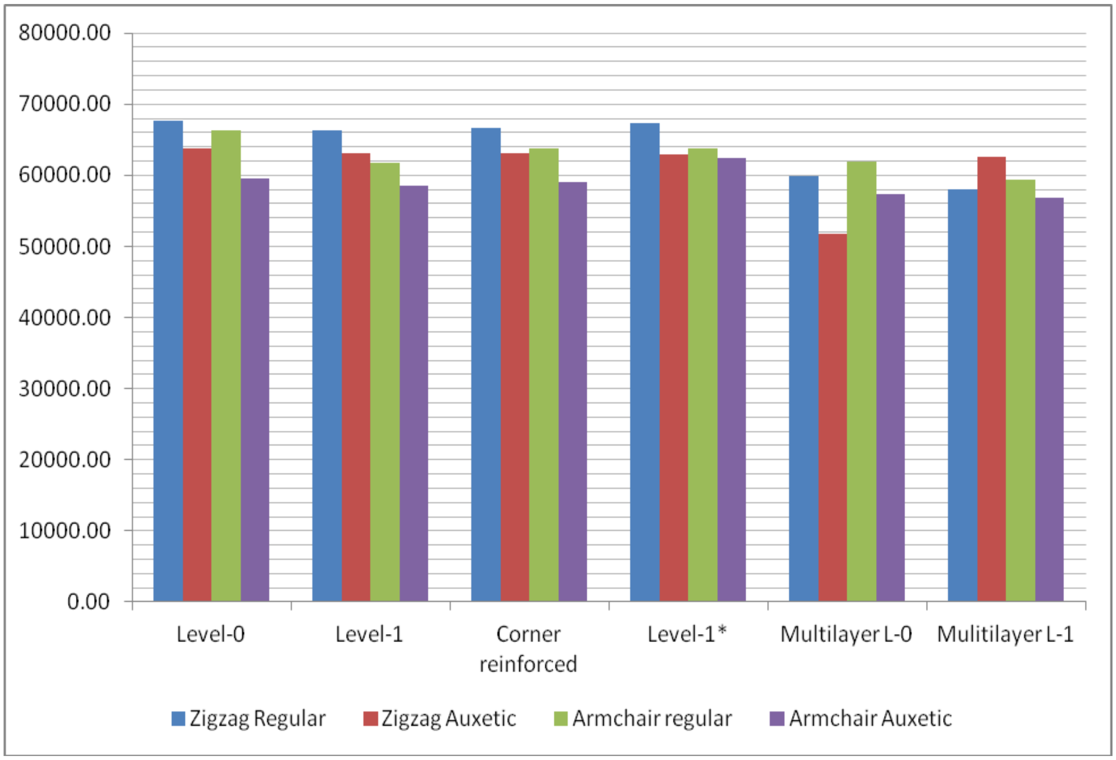


Figure B1: Comparison of sound pressure levels of all structures

Appendix C

Comparison of Zigzag and armchair configuration structures

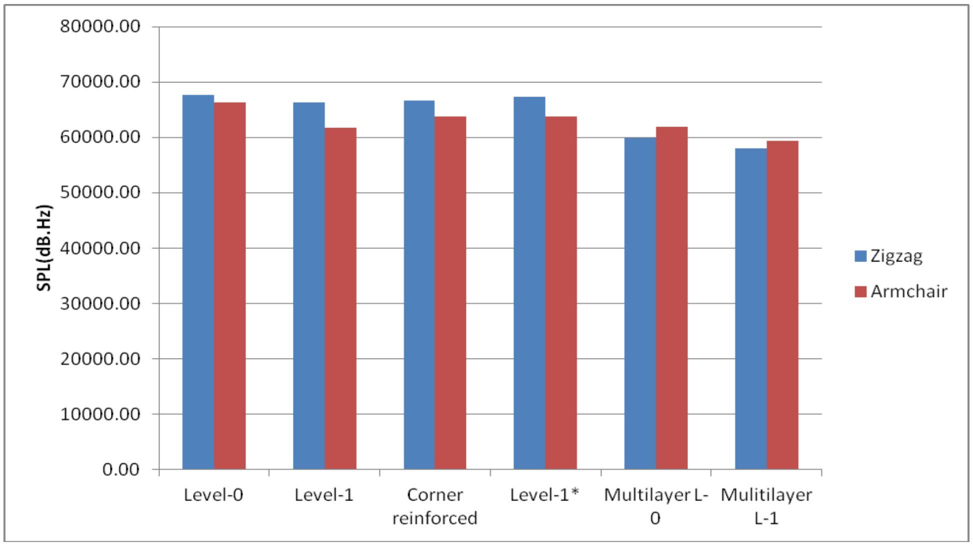


Figure.C1:.Regular honeycomb structures

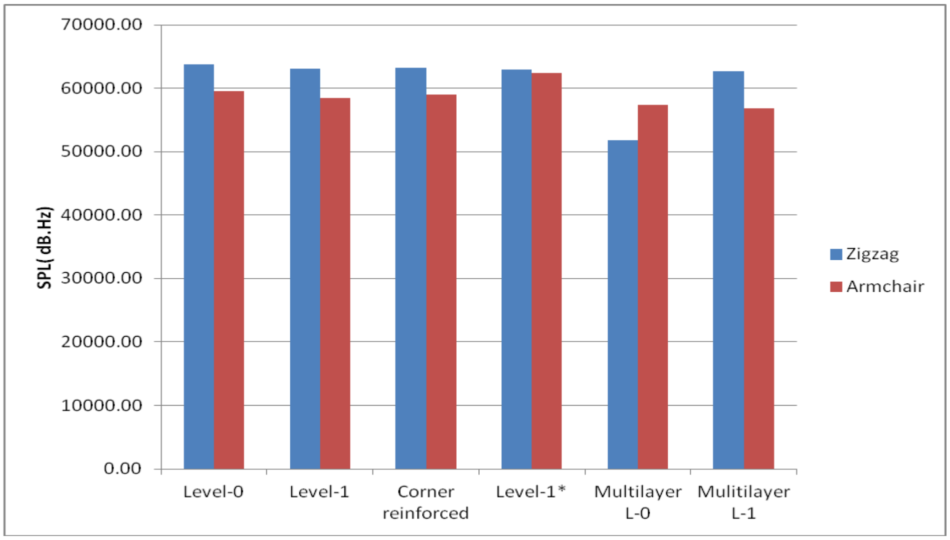


Figure C2:Auxetic honeycomb structures

Appendix D

Comparison of regular and auxetic structures

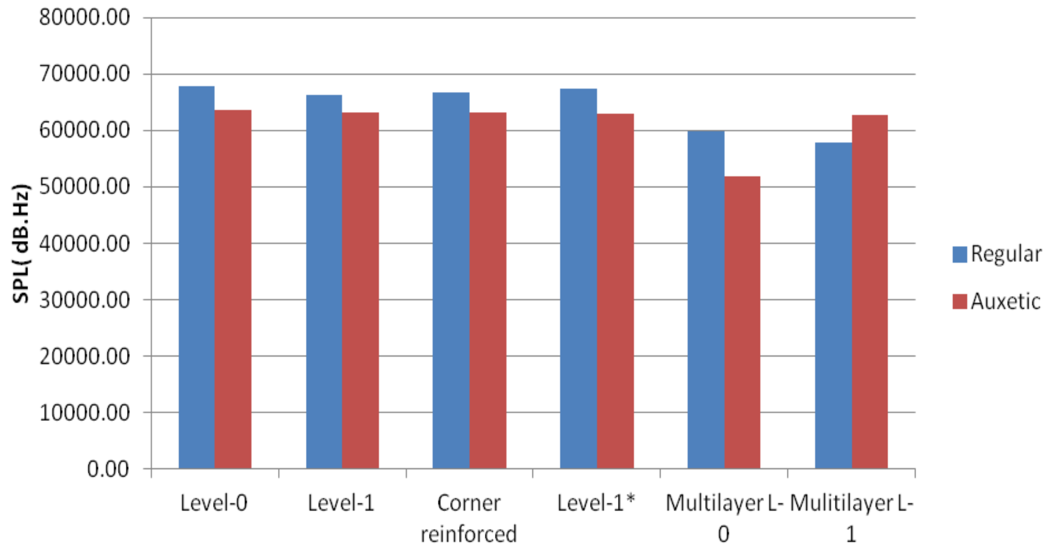


Figure D1: Zigzag configuration

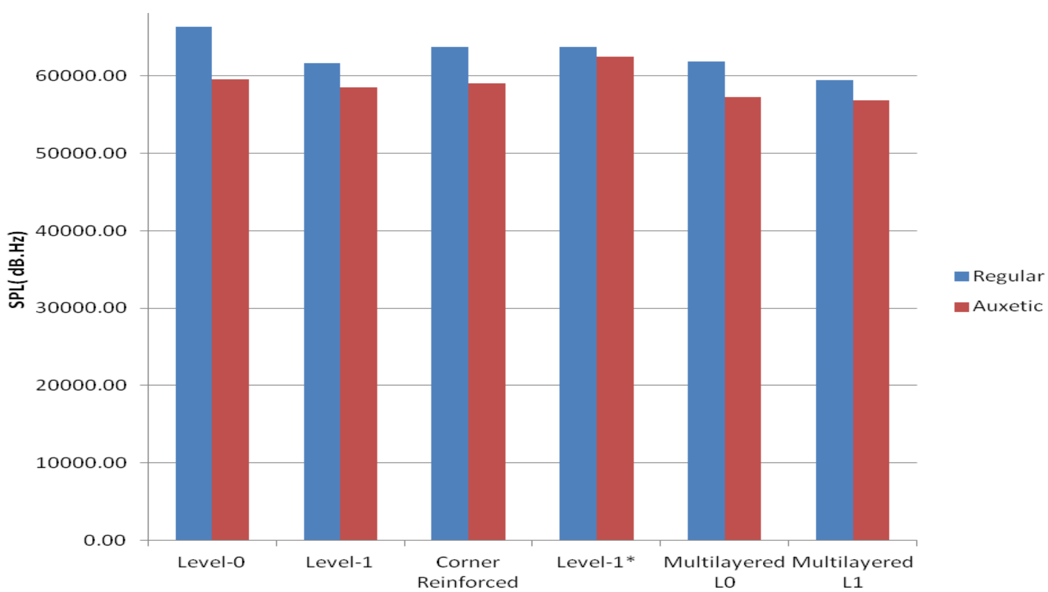


Figure.D2:Armchair configuration

Appendix E

Aspect Ratio of Various Structures

Table E1.Zigzag Regular Honeycombs

Structure	Length of the shortest link, L (mm)	Thickness of the link, t (mm)	Aspect ratio(L/t)
L-0	33.332	3.1860	10.46
L-1	11.111	0.8248	13.47
Corner reinforced	11.111	1.2886	8.62
Level-1*	11.11	1.1128	9.98
Multilayered L-0	24.9990	2.3470	10.65
Multilayered L-1	8.3330	0.6151	13.55
L-2	3.704	0.2570	14.41

TableE2:.Zigzag Auxetic Honeycombs

Structure	Length of the shortest link, L (mm)	Thickness of the link, t (mm)	Aspect ratio(L/t)
L-0	33.3320	2.5580	13.03
L-1	11.1110	0.6576	16.90
Corner reinforced	11.1110	1.8350	6.06
Level-1*	11.1110	0.8467	13.12
Multilayered L-0	24.9990	1.8515	13.50
Multilayered L-1	8.3330	0.5074	16.42

Table E3:.Armchair configuration regular honeycomb

Structure	Length of the shortest link, L (mm)	Thickness of the link, t (mm)	Aspect ratio(L/t)
L-0	14.43	2.4880	5.80
L-1	4.81	0.6801	7.07
Corner reinforced	9.62	1.0689	9.00
Level-1*	4.81	0.9350	5.15
Multilayered L-0	7.22	1.2466	5.79
Multilayered L-1	2.41	0.3404	7.07

Table E4:.Armchair configuration auxetic honeycomb

Structure	Length of the shortest link, L (mm)	Thickness of the link, t (mm)	Aspect ratio(L/t)
L-0	28.8670	1.8621	15.50
L-1	9.6220	0.5341	18.02
Corner reinforced	9.6220	1.3988	6.88
Level-1*	9.6220	0.7022	13.70
Multilayered L-0	14.4330	0.9340	15.45
Multilayered L-1	4.8110	0.2674	17.99

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