A comparative study of vibrational characteristics of carbon fiber composite sandwich plates with truss-cores of different lattice structures.

A thesis submitted to the department of Mechanical and Chemical Engineering (MCE), Islamic University of Technology (IUT), in the partial fulfillment of the requirement for the degree of Bachelor in Science in Mechanical Engineering.

Prepared by

Mehedi Hassan (121404)

Md. Abu Nayeem (121405)

Supervised by

Dr. Md. Zahid Hossain

Department of Mechanical and Chemical Engineering (MCE)
Islamic University of Technology (IUT)
Organization of Islamic Cooperation (OIC)

Contents

CERTIFICATE OF RESEARCH

The thesis title “A comparative study of vibrational characteristics of carbon fiber composite sandwich plates with truss-cores of different lattice structures” submitted by Mehedi Hassan (121404) and Md. Abu Nayeem (121405), has been accepted as satisfactory in partial fulfillment of the requirement for the Degree of Bachelor of Science in Mechanical Engineering on November, 2016.

Supervisor

____

Dr. Zahid Hossain

Professor

Department of Mechanical and Chemical Engineering (MCE)

Islamic University of Technology (IUT)

Head of the Department

____

Prof. Dr. A. K. M. Sadrul Islam

Department of Mechanical and Chemical Engineering (MCE)

DECLARATION

This is to certify that the work presented in this thesis is an outcome of experiment and research carried out by the authors under the supervision of Dr. Zahid Hossain.

Author

Mehedi Hassan (121404)

Md. Abu Nayeem (121405)

Supervisor

Dr. Zahid Hossain

Professor

Department of Mechanical and Chemical Engineering (MCE)

ACKNOWLEDGEMENTS

The thesis was carried out by the author themselves under the close supervision and guidance of **Dr. Md. Zahid Hossain**, Department of Mechanical and Chemical Engineering (MCE), Islamic University of Technology (IUT). We would like to thank him from the deepest of our hearts, for helping us all the way. He dedicated his valuable time and effort to solve our problems and guided us in such a nice way that is really beyond imagination. His vast knowledge in the field of vibration also enhanced our venture to a great extent.

ABSTRACT

The effective vibrational characteristics of sandwich plates with truss-cores of pyramidal truss lattice structure and reciprocal double-pyramidal truss lattice structure made of carbon fiber composite have been investigated theoretically in this paper. Analytical models were developed using ANSYS® finite element analysis software. Mode shapes and natural frequencies were investigated in both structures using ANSYS® Modal and a frequency versus mode curve was generated for both of the cases. Modal analysis was also done in both structures at different fiber orientations and a natural frequency versus fiber orientation curve was generated for each cases. Frequency response analysis was done using ANSYS® Harmonic and an amplitude (in decibel) versus frequency curve was generated for both of the lattice structures. At last, all of the results for both pyramidal truss lattice structure and reciprocal double-pyramidal truss lattice structure were compared and a conclusion was drawn depending on the results obtained from the investigation.

OBJECTIVES

- To simulate two models of sandwich plates with truss-cores of pyramidal truss lattice structure and reciprocal double-pyramidal truss lattice structure made up of carbon fiber composite material.
- To analyze different effective vibrational characteristics of both of the structures.
- As we all know, premature failure of critical components can be caused if the structures served under the resonant vibration. So our main target is to reduce the amplitude of this vibration.
- To improve the crushing strength of the structure, which is higher in truss-cored sandwich plates than honeycomb core construction.

Chapter One

Background & Introduction

1.1 INTRODUCTION

In the flow of recent scientific advancement, manufacturing of truss lattice structure seem to critically extent their possibilities of application. During the recent few years, a variety of metallic and polymeric foams have been produced for a wide range of potential applications such as the cores of sandwich panels and various automotive parts. A typical aim is to develop lightweight structures that are adequately stiff and strong. Sandwich plates with truss cores, made of carbon fiber composite, are investigated in this project, which possess certain advantages over plain sandwich plates. It uses truss cores, which increases the load bearing capacity of the structure. It also improves the strength to weight ratio (e.g. specific strength) and stiffness. Carbon fiber composite is used here instead of metal alloy since weight can be further reduced without compromising the strength of the structure. Moreover, carbon fiber composite has some advantages in mechanical properties under compression, shear, bending and impact loading conditions. The initial works on the analysis of fiber-reinforced composite materials have been developed by Adams et al. Two dimensional analysis of sandwich plates with truss cores was theoretically investigated by Nathan et al.

1.2 NATURAL FREQUENCY

If a system, after an initial disturbance, is left to vibrate on its own, the frequency with which it oscillates without external forces is known as its natural frequency. As will be seen later, a vibratory system having n degrees of freedom will have, in general, n distinct natural frequencies of vibration.

Free vibrations of an elastic body are called natural vibrations and occur at a frequency called the natural frequency. Natural vibrations are different from forced vibrations which happen at frequency of applied force (forced frequency). If forced frequency is equal to the natural frequency, the amplitude of vibration increases many fold. This phenomenon is known as resonance. It occurs when a mechanical system is set off with an initial input and then allowed to vibrate freely. Examples of this type of vibration are pulling a child back on a swing and then letting go or hitting a tuning fork and letting it ring. The mechanical system will then vibrate at one or more of its "natural frequency" and damp down to zero.

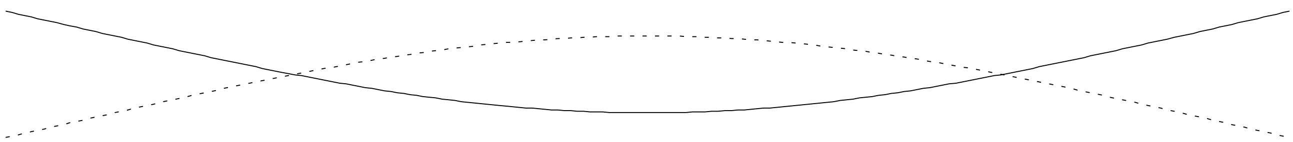
1.3 MODE AND MODE SHAPES

Simply, mode is the *shape* of the vibration. A mode is a standing wave state of excitation, in which all the constituents of the system will be affected sinusoidally under a defined fixed vibration.

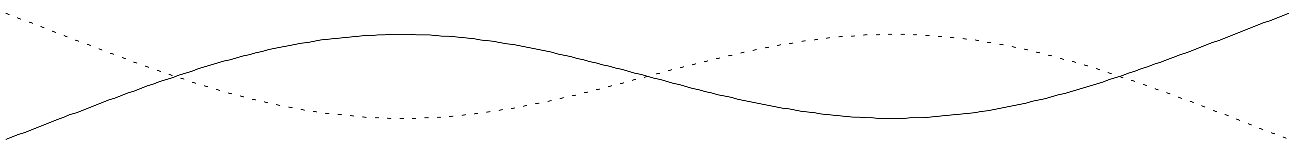
Any complex body (i.e. more complicated than a single mass on a simple spring) can vibrate in many different ways. These different ways of vibrating will each have their own frequency, that frequency determined by moving mass in that mode, and the restoring force which tries to return that specific distortion of the body back to its equilibrium position.

It can be somewhat difficult to determine the shape of these modes. For example one cannot simply strike the object or displace it from equilibrium, since not only the one mode liable to be excited in this way. Many modes will tend to excited, and all to vibrate together. The shape of the vibration will thus be very complicated and will change from one instant to the next.

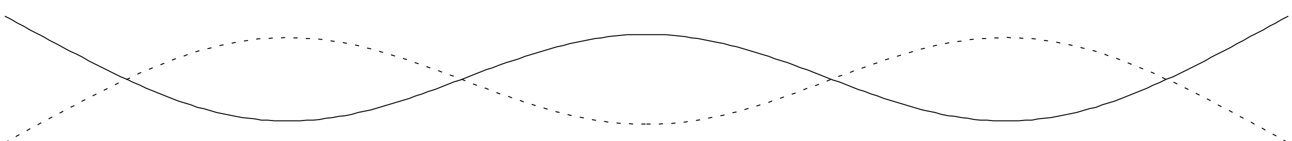
A mode of vibration is characterized by a modal frequency and a mode shape. It is numbered according to the number of half waves in the vibration. For example, if a vibrating beam with both ends pinned displayed a mode shape of half of a sine wave (one peak on the vibrating beam) it would be vibrating in mode 1. If it had a full sine wave (one peak and one trough) it would be vibrating in mode 2. The modes of the string have the special feature that the frequencies of all of modes are simply integer multiples of each other. The n^{th} mode has a frequency of n times the frequency of the first mode. This is not a general feature of modes. In general the frequencies of the modes have no simple relation to each other. As an example let us look at the modes of a vibrating bar free bar. In the figure below, we plot the shape of the first five modes of a vibrating bar, together with the frequencies of the five modes. Again the solid lines are the shape of the mode on maximum displacement in one direction and the dotted the shape on maximum displacement in the other direction. Note that these are modes where the bar is simply vibrating, and not twisting. If one thinks about the bar being able to twist as well, there are extra modes. For a thin bar, the frequencies of these modes tend to be much higher than these lowest modes discussed here. However the wider the bar, the lower the frequencies of these modes with respect to the vibrational modes.



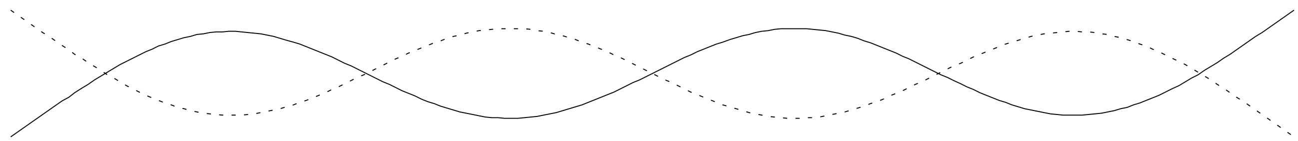
Mode 1



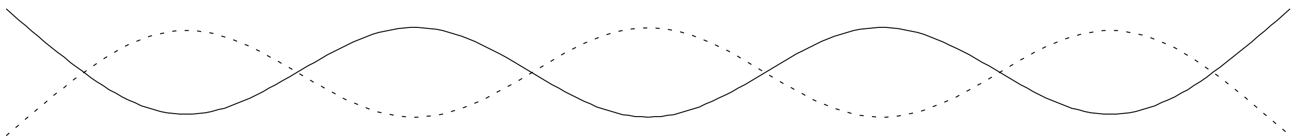
Mode 2



Mode 3



Mode 4



Mode 5

1.4 HARMONIC ANALYSIS

In music, if a note has frequency f, integer multiples of that frequency, 2f, 3f, 4f and so on, are known as harmonics. As a result, the mathematical study of overlapping waves is called harmonic analysis. Harmonic analysis is a diverse field including such branches as Fourier series, isospectral manifolds (hearing the shape of a drum), and topological groups. Signal processing, medical imaging, and quantum mechanics are three of the fields that use harmonic analysis extensively. Although harmonic motion is simplest to handle, the motion of many vibratory systems is not harmonic. Fortunately, any periodic function of time can be represented by Fourier series as an infinite sum of sine and cosine terms.

If x(t) is a periodic function with period τ, its Fourier series representation is given by

$$
\begin{aligned}
x(t) &= \frac{a_0}{2} + a_1 \cos \omega t + a_2 \cos 2\,\omega t + \cdots \\
&\quad + b_1 \sin \omega t + b_2 \sin 2\,\omega t + \cdots \\
&= \frac{a_0}{2} + \sum_{n=1}^{\infty} (a_n \cos n\omega t + b_n \sin n\omega t)
\end{aligned}
$$

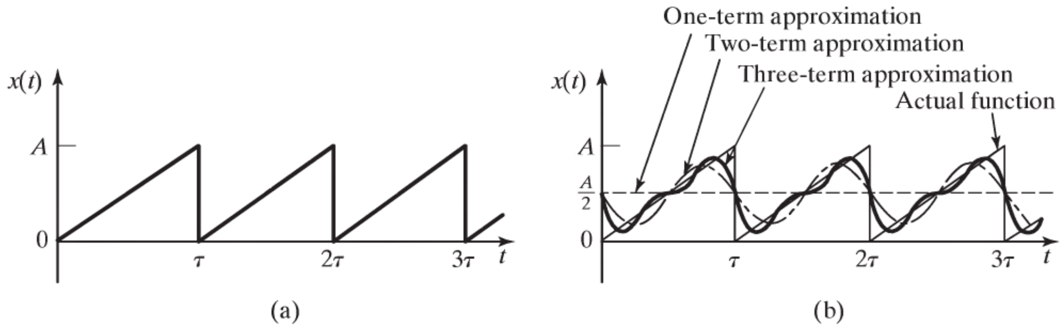


Fig. A periodic function

where $\omega = 2\pi/\tau$ is the fundamental frequency and a_0, a_1 a_2, ..., b_1 b_2, ... are constant coefficients.

1.5 OUTLINE OF THE ANALYSIS

At first the investigation was done by computer simulation. The software used for this purpose is ANSYS®. Here the model of both the sandwich plate with pyramidal truss core and reciprocal double pyramidal truss core both were done using ANSYS® design modeler. Then the composite material is modelled using the ANSYS® COMPOSITE POST (Pre). Here the properties of the composite material were taken from reference [1]. And the unknown properties were assumed from the ANSYS® material library. Then modal analysis and harmonic analysis was for a particular force. Then we have plotted the obtained results in graphs in Microsoft® Excel 2013 for comparison. The graph which were plotted for the results are:

- Total Deformation vs. mode for each structure
- Total Deformation vs. mode frequency from harmonic analysis
- Mode frequency vs. orientation of the carbon fiber for composite material truss core.
- Comparison of characteristics of the best structure with the different lightweight materials.
- Cost analysis and break even.

Chapter Two

Materials & Modelling

2.1 MATERIALS

The material which were used for investigation is—

Plates: unidirectional carbon/epoxy (T700/3234) laminate

Truss: unidirectional carbon/epoxy (T700/3234) rods

2.1.1 CARBON FIBRE COMPOSITE

Carbon fiber reinforced polymer, carbon fiber reinforced plastic or carbon fiber reinforced thermoplastic, is an extremely strong and light fiber-reinforced plastic which contains carbon fibers. CFRPs are composite materials. In this case the composite consists of two parts: a matrix and a reinforcement. In CFRP the reinforcement is carbon fiber, which provides the strength. The matrix is usually a polymer resin, such as epoxy, to bind the reinforcements together. Because CFRP consists of two distinct elements, the material properties depend on these two elements. In our experiment epoxy is used as the matrix that is thermosetting plastic. The properties of the composite which were used in the analysis were developed by using the hot press molding technique that were cured at 130°C for 1.5 h under a nominal pressure of 0.5 MPa on a mold plate. The detailed properties of unidirectional carbon/epoxy composite laminate used in our analysis are listed below:

Symbol	*Value*	*Property*
E_{11}	119 GPa	Longitudinal stiffness
E_{22}	8.7 GPa	Transverse stiffness
E_{33}	8.7 GPa	Out-of-plane stiffness
υ_{12}, υ_{13}	0.32	Poisson's ratio
υ_{23}	0.3	Poisson's ratio
G_{12}, G_{13}	4 GPa	Shear modulus
G_{23}	3 GPa	Shear modulus
ρ	1560 kg/m^3	Density

Table: The material properties of unidirectional carbon/epoxy (T700/3234) laminate

2.2 MODELLING

Hybrid sandwich panels were arranged in the form of structure with one edge fixed and with the others free. The dimensions of the specimens were illustrated as following. The length a = 270 mm, the width b = 98 mm and the thickness h = 17 mm, the length of fixed area f = 15 mm, so the effective length of the structure a - f = 255 mm. The span between the truss vertices k = 7 mm, the radius of truss member d = 1.25 mm, the inclined angle 45°, the length of truss member l = 21.2 mm, the height of truss = 15 mm.

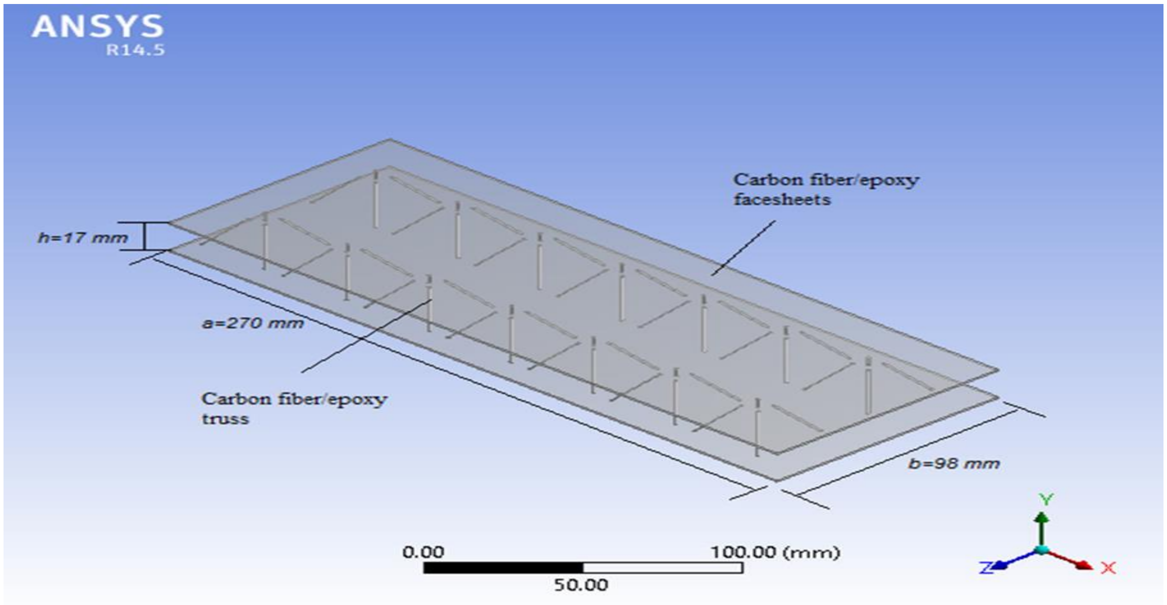


Fig. Schematic illustration of single pyramidal truss core sandwich plates

Fig. Schematic illustration of a single pyramidal truss lattice

Reciprocal double-pyramidal truss core sandwich plate arranged in the form of structure with one edge fixed and with the others free. The dimensions of the specimens were illustrated as following. The length a = 270 mm, the width b = 98 mm and the thickness h = 17 mm, the length of so the effective length of the structure a - f = 255 mm. The radius of truss member d = 1.25 mm, the inclined angle 45°, the length of truss member l = 21.2 mm, the height of truss = 15 mm.

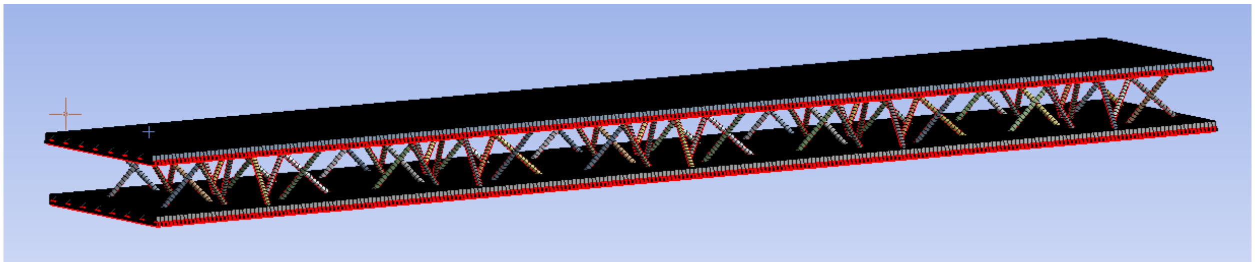


Fig. Schematic illustration of reciprocal double-pyramidal truss core sandwich plates

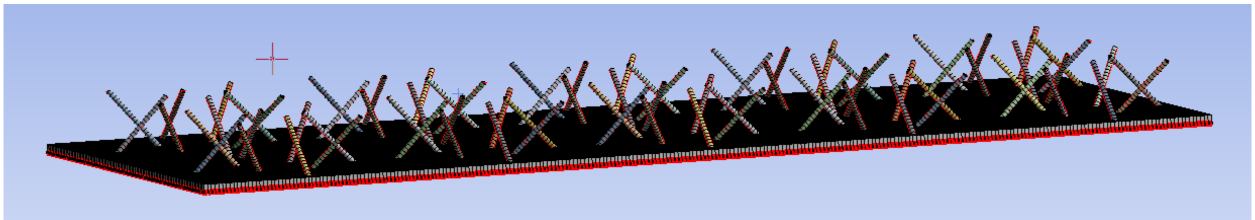


Fig. Schematic illustration of same structure without the upper plate

In the first configuration there were 14 units of truss lattice. In the second configuration the number of truss unit were decreased to 10 units to accommodate the truss in the available space each,consisting of 8 truss member. Here the highest distance between the two consecutive truss member were increased to 32.527 mm and the span between the truss vertices incresed to 13.313 mm. All the other dimensions remain same

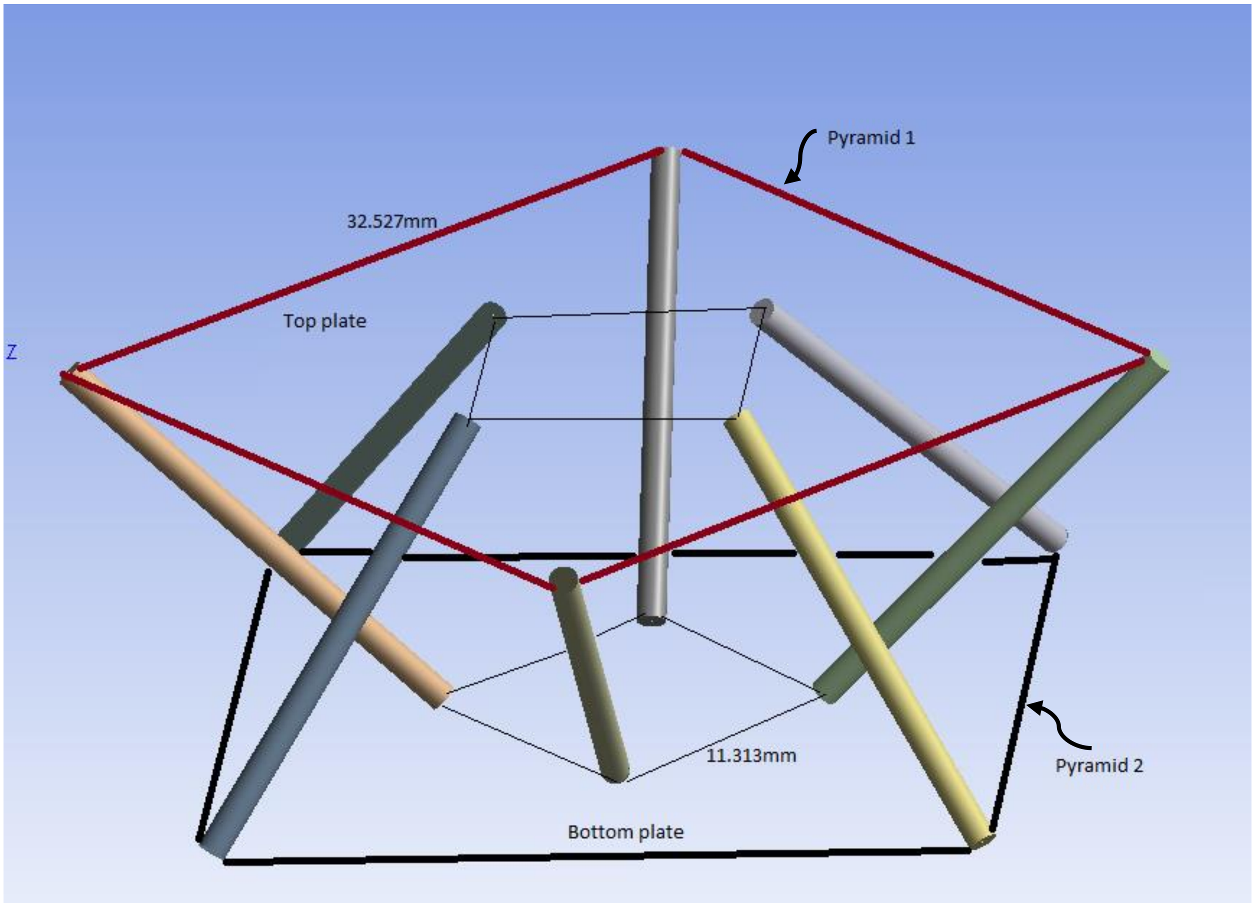


Fig. Schematic illustration of a single reciprocal double-pyramidal truss lattice

Chapter Three

Meshing

3.1 MESHING

ANSYS® Meshing is a general-purpose, intelligent, automated high-performance product. It produces the most appropriate mesh for accurate, efficient multiphysics solutions. A mesh well suited for a specific analysis can be generated with a single mouse click for all parts in a model. Full controls over the options used to generate the mesh are available for the expert user who wants to fine-tune it. The power of parallel processing is automatically used to reduce the time you have to wait for mesh generation. Mesh generation is the practice of generating a polygonal or polyhedral mesh that approximates a geometric domain. Three-dimensional meshes created for finite element analysis need to consist of tetrahedra, pyramids, prisms or hexahedra. Those used for the finite volume method can consist of arbitrary polyhedra. Those used for finite difference methods usually need to consist of piecewise structured arrays of hexahedra known as multi-block structured meshes. A mesh is otherwise a discretization of a domain existing in one, two or three dimensions.

3.2 TYPES OF MESHING

3.2.1 TWO DIMENSINAL

There are two types of two-dimensional cell shapes that are commonly used. These are the triangle and the quadrilateral.

Computationally poor elements will have sharp internal angles or short edges or both.

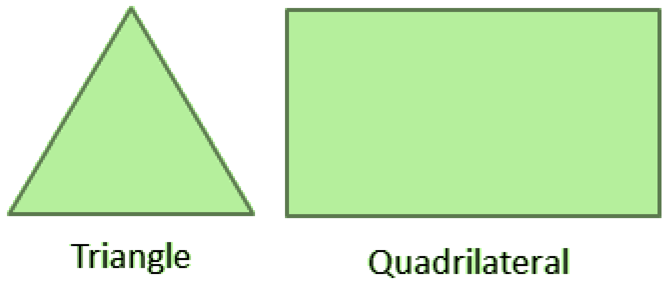


Fig. Basic two-dimensional Cell shapes

Triangle

This cell shape consists of 3 sides and is one of the simplest types of mesh. A triangular surface mesh is always quick and easy to create. It is most common in unstructured grids.

Quadrilateral

This cell shape is a basic 4 sided one as shown in the figure. It is most common in structured grids. Quadrilateral elements are usually excluded from being or becoming concave.

3.2.2 THREE-DIMENSIONAL

The basic 3-dimensional element are the tetrahedron, quadrilateral pyramid, triangular prism, and hexahedron. They all have triangular and quadrilateral faces.

Extruded 2-dimensional models may be represented entirely by prisms and hexahedra as extruded triangles and quadrilaterals.

In general, quadrilateral faces in 3-dimensions may not be perfectly planar. A nonplanar quadrilateral face can be considered a thin tetrahedral volume that is shared by two neighboring elements.

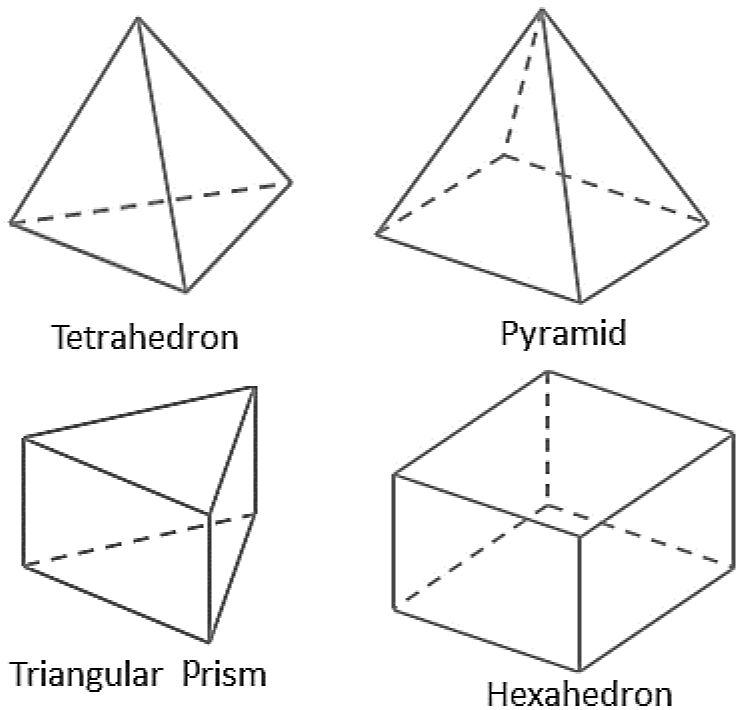


Fig. Basic three-dimensional cell shapes

Tetrahedron

A tetrahedron has 4 vertices, 6 edges, and is bounded by 4 triangular faces. In most cases a tetrahedral volume mesh can be generated automatically.

Pyramid

A quadrilaterally-based pyramid has 5 vertices, 8 edges, bounded by 4 triangular and 1 quadrilateral face. These are effectively used as transition elements between square and triangular faced elements and other in hybrid meshes and grids.

Triangular prism

A triangular prism has 6 vertices, 9 edges, bounded by 2 triangular and 3 quadrilateral faces. The advantage with this type of layer is that it resolves boundary layer efficiently.

Hexahedron

A hexahedron, a topological cube, has 8 vertices, 12 edges, bounded by 6 quadrilateral faces. It is also called a hex or a brick. For the same cell amount, the accuracy of solutions in hexahedral meshes is the highest.

The pyramid and triangular prism zones can be considered computationally as degenerate hexahedrons, where some edges have been reduced to zero. Other degenate forms of a hexahedron may also be represented.

3.3 MESHING OF MODELS

Meshing of the model is done in ANSYS modal analysis. Meshing is done in the following way:

3.3.1 SETTING CONTACT REGION AND CONTACTS

There are 80 truss member and each of them has surface contact with both the top and bottom plate. So the total number of total contact region is 160 and we assumed them to have a no separation joint.

3.3.2 MESH CONNECTION

We have used the automatic mesh connection where we have the freedom to set the element size and we set it to .3 mm for faster computation of meshing.

3.3.3 MESH GENERATION

The physics preference of meshing is mechanical and we need to optimize the mesh size for faster and reliable computation. The mesh sizing is done in the following way:

Use Advanced Size Function	On: Curvature
Relevance Center	Coarse
Initial Size Seed	Active Assembly
Smoothing	Low
Transition	Fast
Span Angle Center	Coarse
Curvature Normal Angle	Default (30.0 °)
Min Size	Default (0.393880 mm)
Max Face Size	Default (1.96940 mm)
Max Size	Default (1.96940 mm)
Growth Rate	Default
Minimum Edge Length	4.71240 mm

No inflation is done on meshing.

3.3.4 MESH RESULT

The following result is obtained through meshing:

Nodes	**77689**
Elements	34544

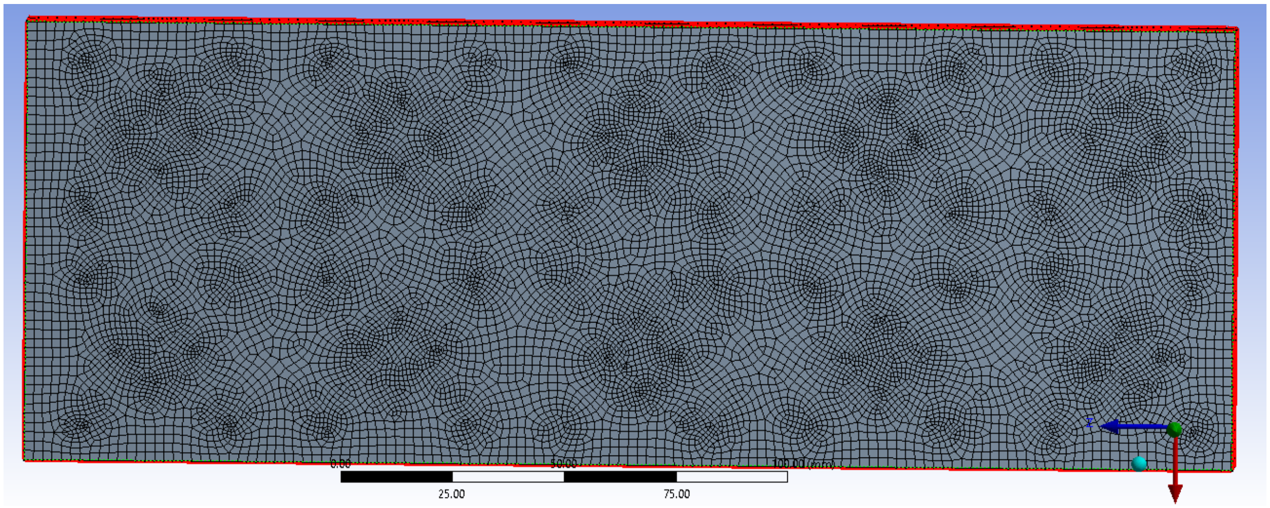


Fig. Meshing of bottom plate of the double pyramid truss core sandwich plate

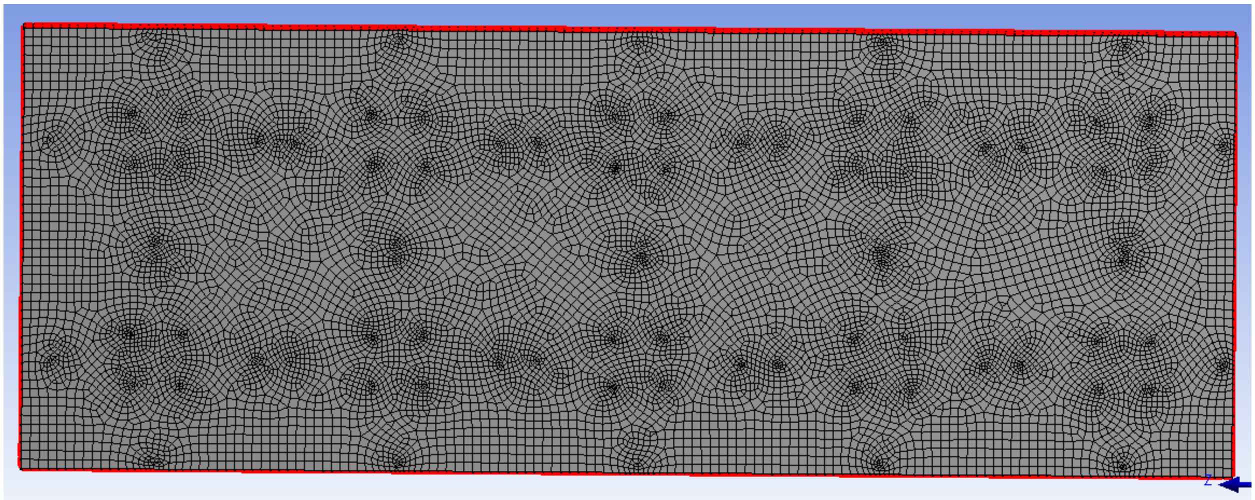


Fig. Meshing of Top plate of the double pyramid truss core sandwich plate

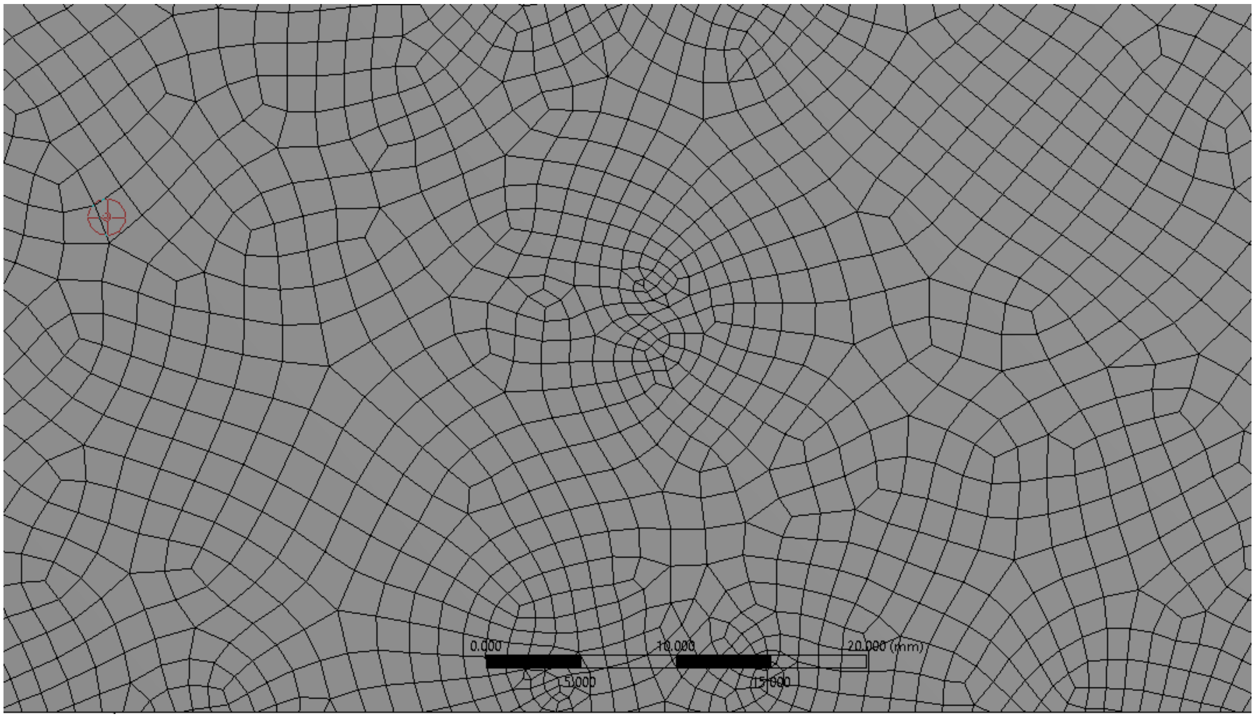


Fig. close shot of a single contact region

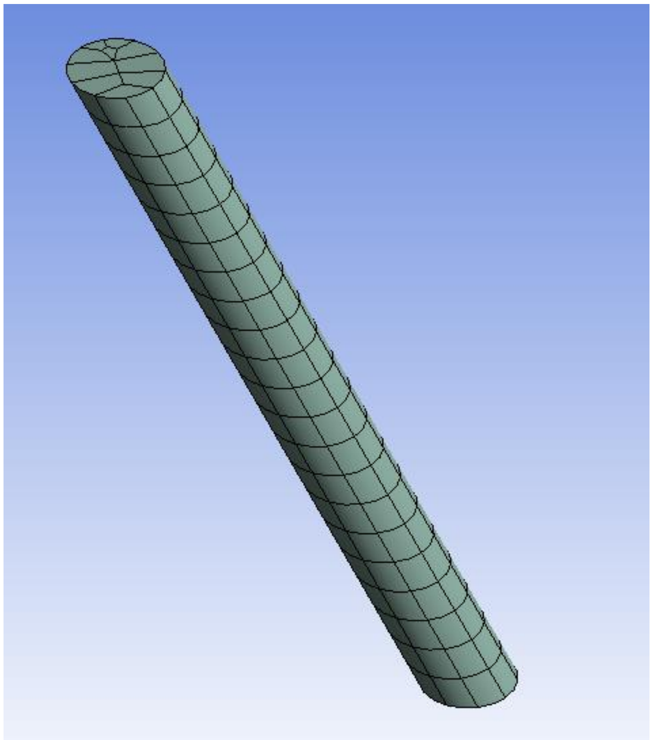


Fig. Mesh of a truss member

Chapter Three

Material Modelling

4.1 COMPOSITE MODELLING

ANSYS doesn't provide with a material library of composite material by default. So we have used an extension of software which is suitable for designing or modelling of composite material known as Ansys Composite Post (ACP).

4.2 MANUAL COORDINATE SYSTEM

Since each truss has a different orientation and fibers are orientated along its length, we have to define 8 manual coordinate systems other than the global coordinate system for each group of truss oriented in a particular direction.

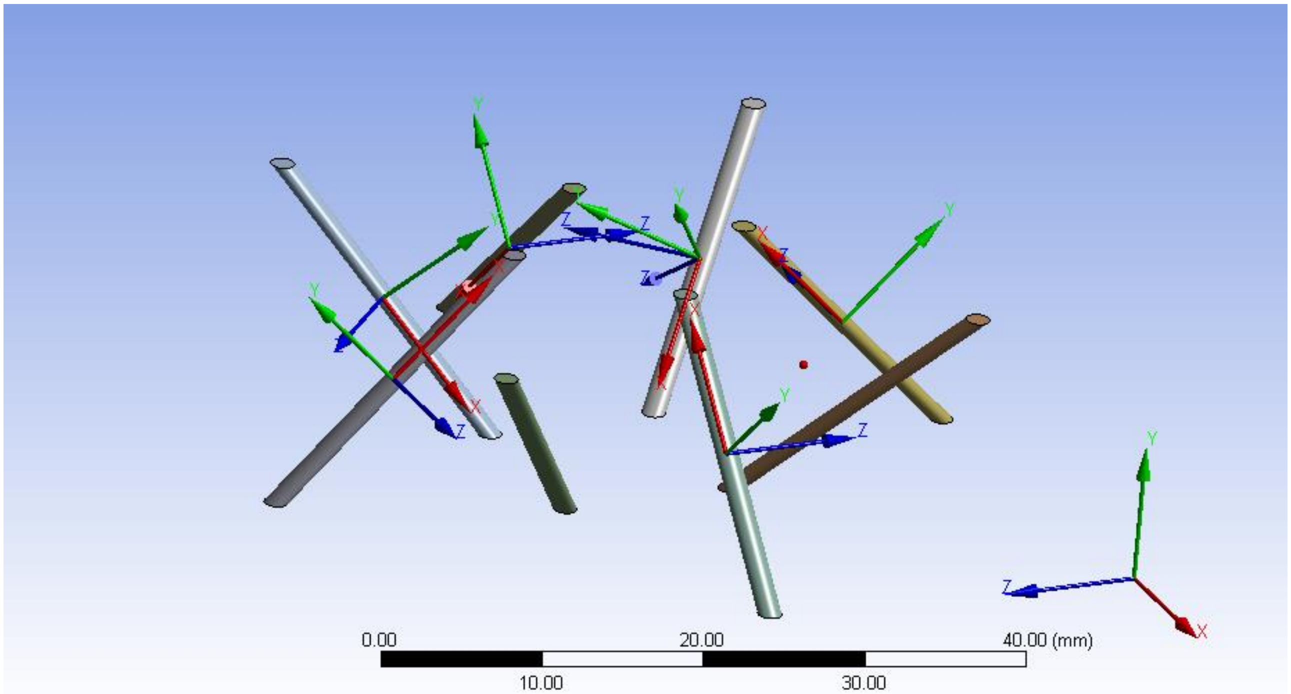


Fig. Manual coordinate systems

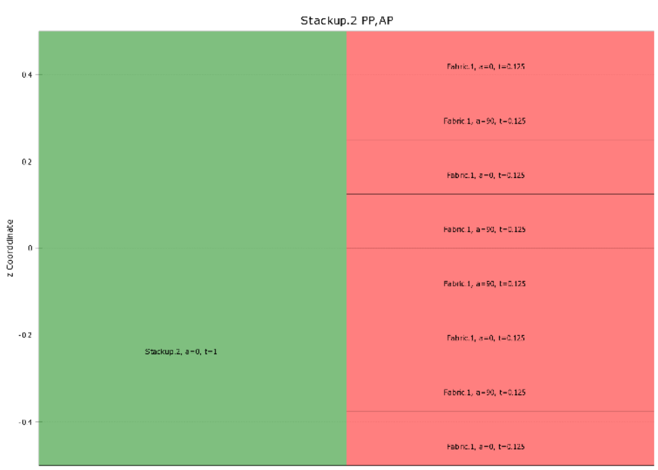
4.3 DEFINING FABRIC

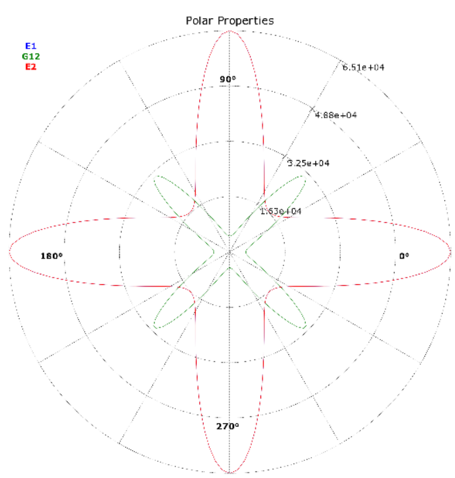
Both the top and bottom plate consists of 8 layer of carbon fiber composite plate oriented in different direction. So in ANSYS ACP we created composite material plate made of carbon fiber epoxy material each have a thickness of .125mm

4.4 CREATING STACKUP

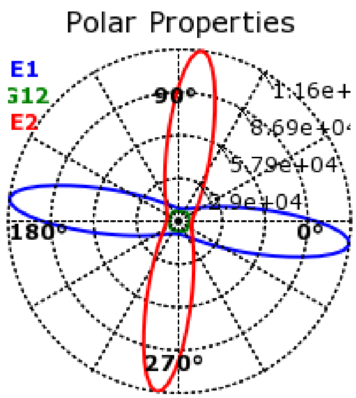
Next stack up of fabric is done to define the construction of top and bottom plate. Stack up is

done in the following way for single pyramidal truss:

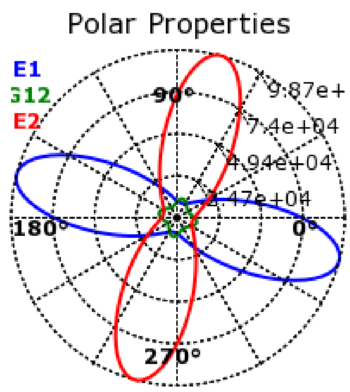




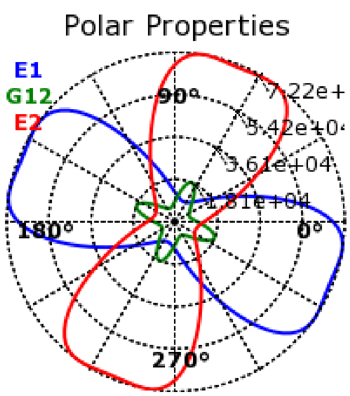
For other type of orientation we got the following polar properties:



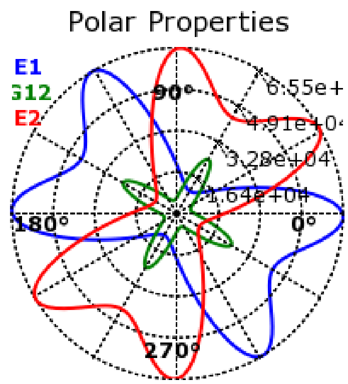
15 degree



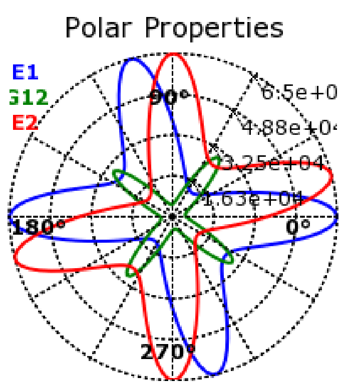
30 degree



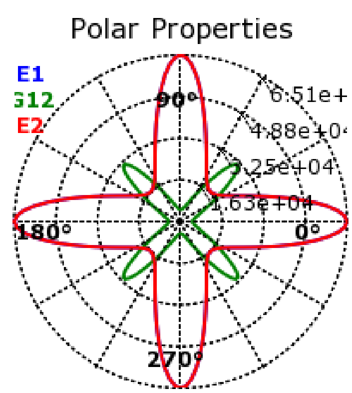
45 degree



60 degree



75 degree



90 degree

Chapter Five

Results & Discussion

5.1 COMPARISON OF BASIC VIBRATION CHARACTERISTICS

The first six natural frequencies for both sandwich plates with truss-cores of single pyramidal truss lattice structure and reciprocal double-pyramidal truss lattice structure made of carbon fiber composite obtained from numerical calculations through simulation are shown in the figure below.

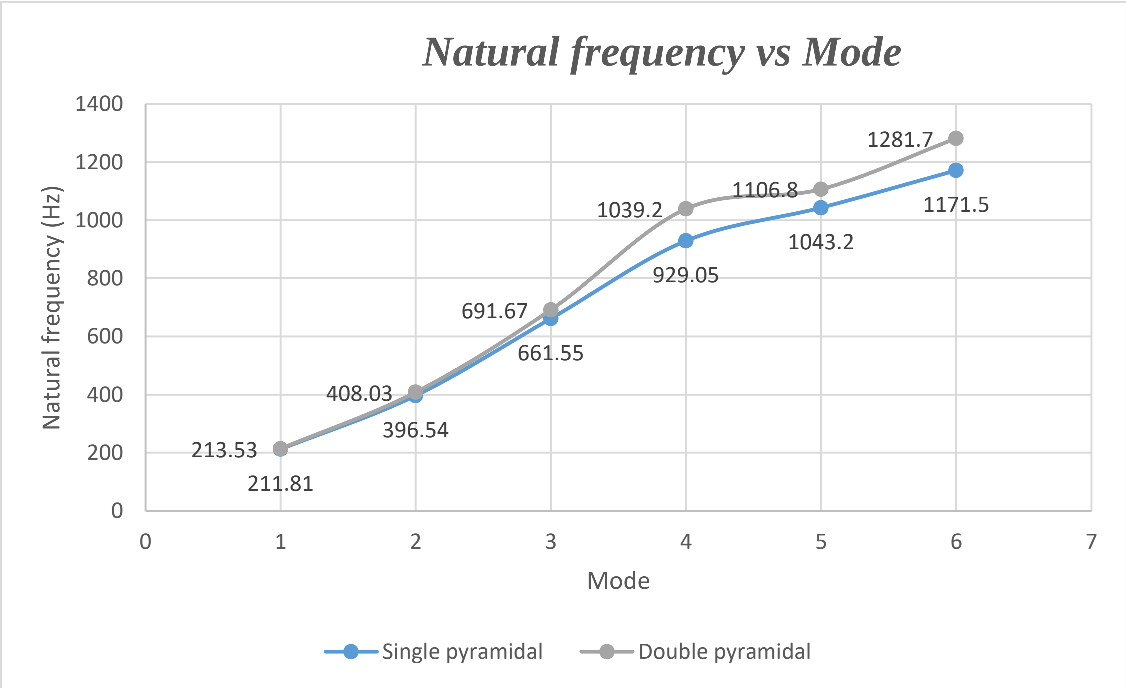
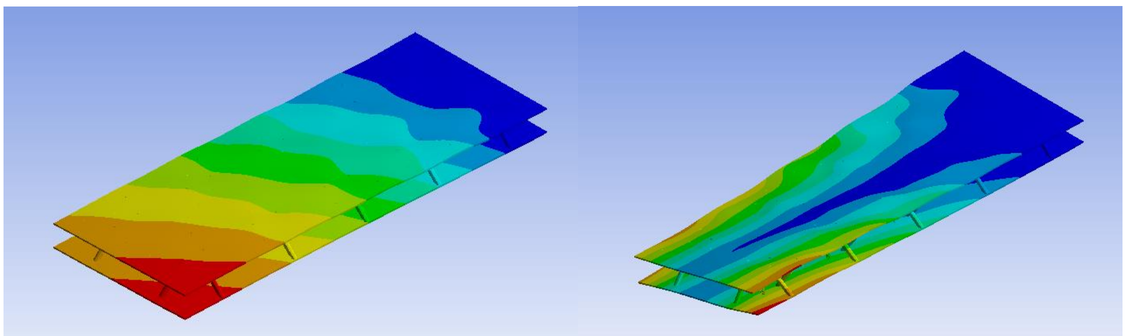


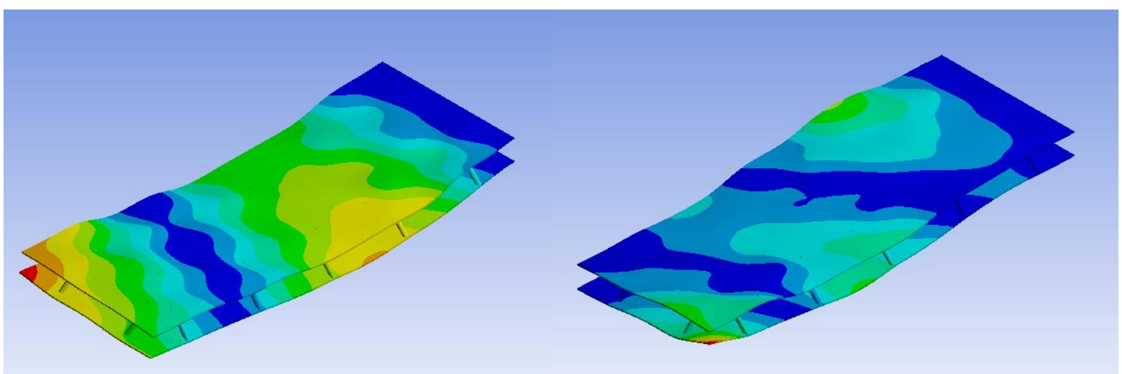
Fig. Natural frequency vs. Mode

As shown in the above figure, the natural frequencies in both cases were somewhat similar for the first three modes and then it started to deviate gradually from each other. Natural frequencies for the double pyramidal structure is higher than that of the single pyramidal one.

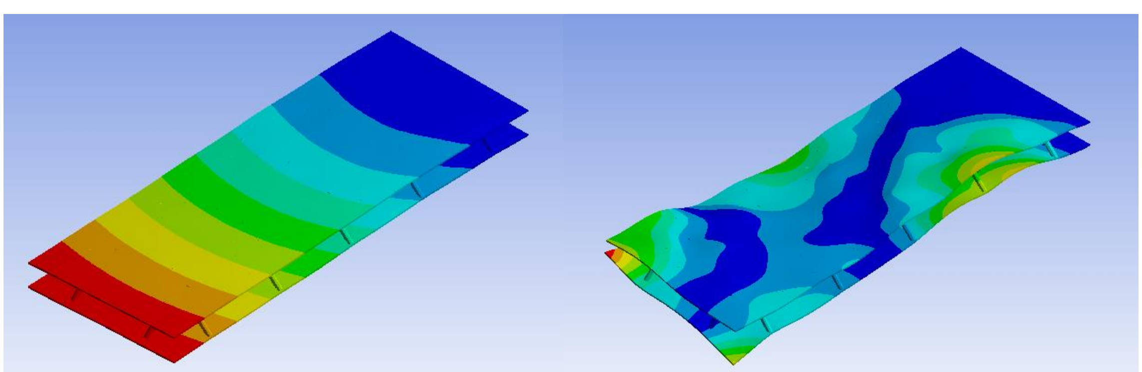
Mode shapes of the two models we are analyzing are similar. So we are presenting mode shape of the reciprocal double-pyramid truss core sandwich plates here.



Mode 1 and 2



Mode 3 and 4



Mode 5 and 6

When we have done the modal analysis on both of the structure and took the data of deformation for each modes, plotted the following curves where we can observe that the total deformation in the structure with reciprocal double-pyramidal truss lattice is lower than that for the structure with single pyramidal truss lattice.

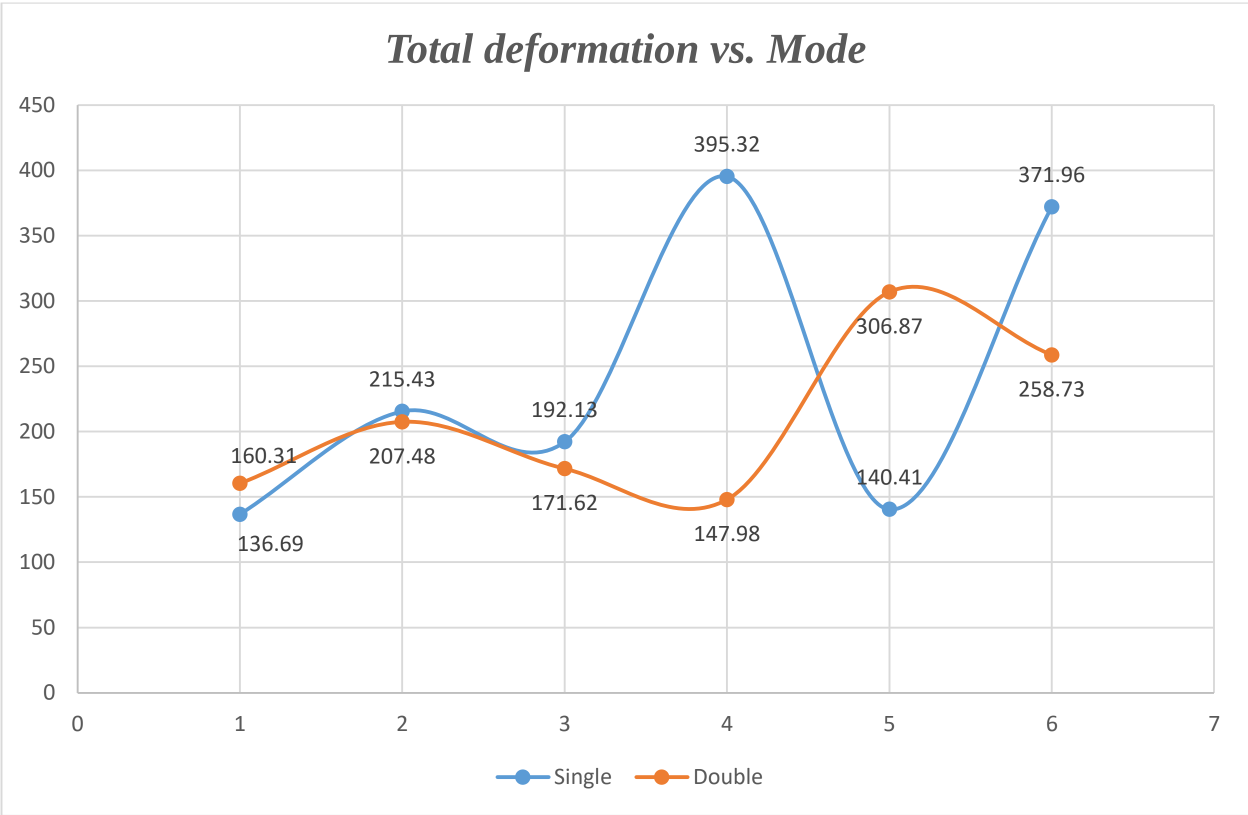


Fig. Total deformation vs. Mode

5.2 VON MISES STRESS COMPARISON FOR STATIC LOAD

von Mises stress were analyzed for both of the structures using ANSYS® Static Structural. Pressure of 10 kPa was applied on the top surface for each and the maximum and minimum stress developed and deformation are given in the tables below.

For structure with reciprocal double-pyramidal truss lattice:

Minimum	6.2347e-002 MPa	0. mm
Maximum	381.56 MPa	4.4729 mm

For structure with single pyramidal truss lattice:

Minimum	1.0575e-002 MPa	0. mm
Maximum	115.75 MPa	1.4586 mm

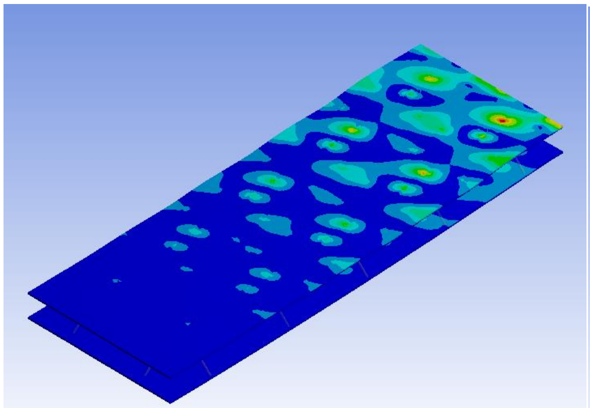


Fig. double pyramidal

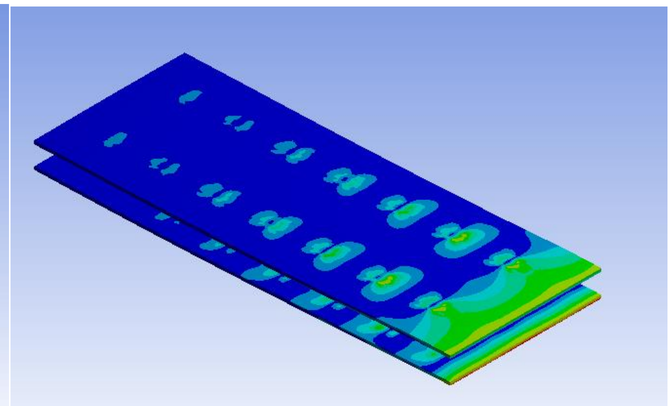


Fig. single pyramidal

As we can observe from the results, the maximum stress developed in the structure with reciprocal double-pyramidal truss lattice is much higher than that for the structure with single pyramidal truss lattice.

5.3 DYNAMIC RESPONSE

The steady state dynamic responses of such structure were operated by finite element analysis on the basis of modal superposition method. The following chart shows the dynamic response of the structure with reciprocal double-pyramidal truss lattice. The amplitude is in decibel and the frequency is in Hertz.

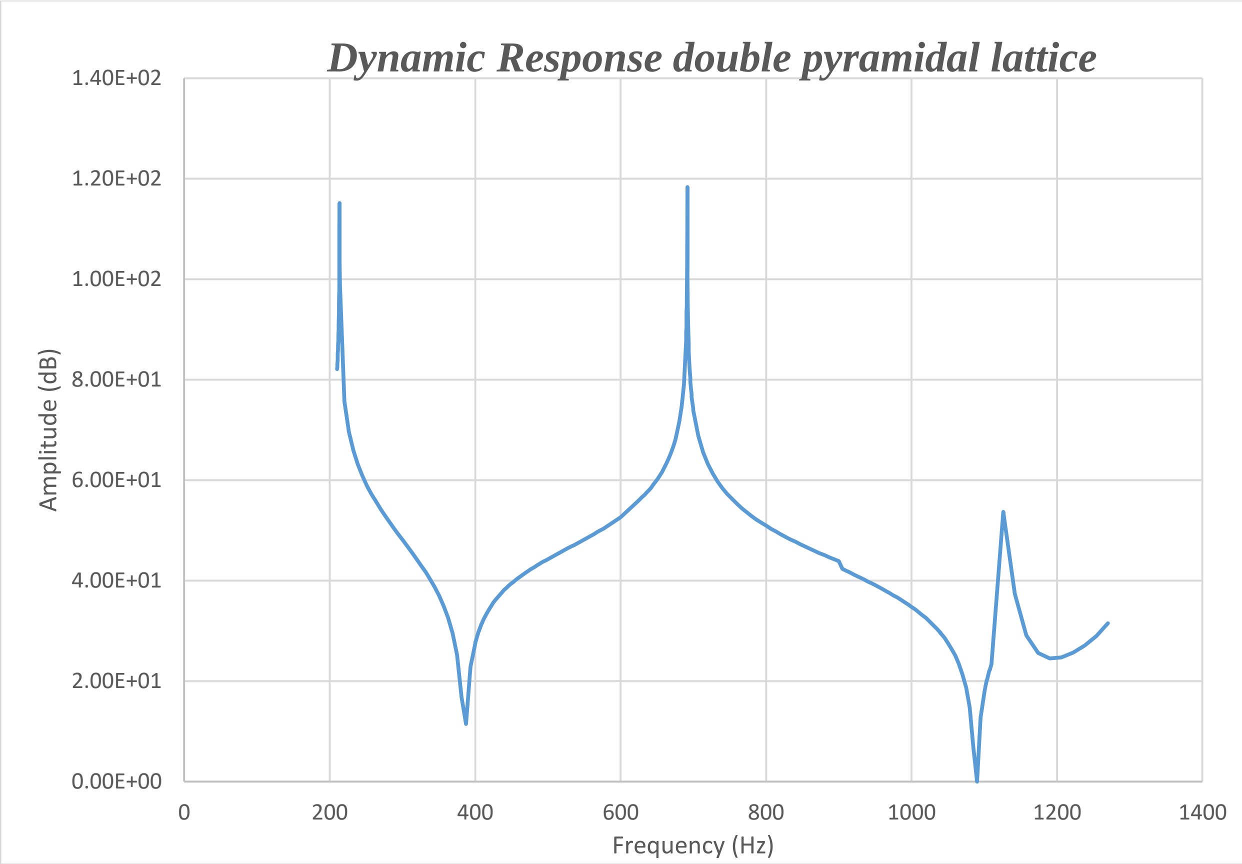


Fig. Dynamic Response double pyramidal lattice

The following chart shows the dynamic response of the structure with single pyramidal truss lattice. The amplitude is in decibel and the frequency is in Hertz.

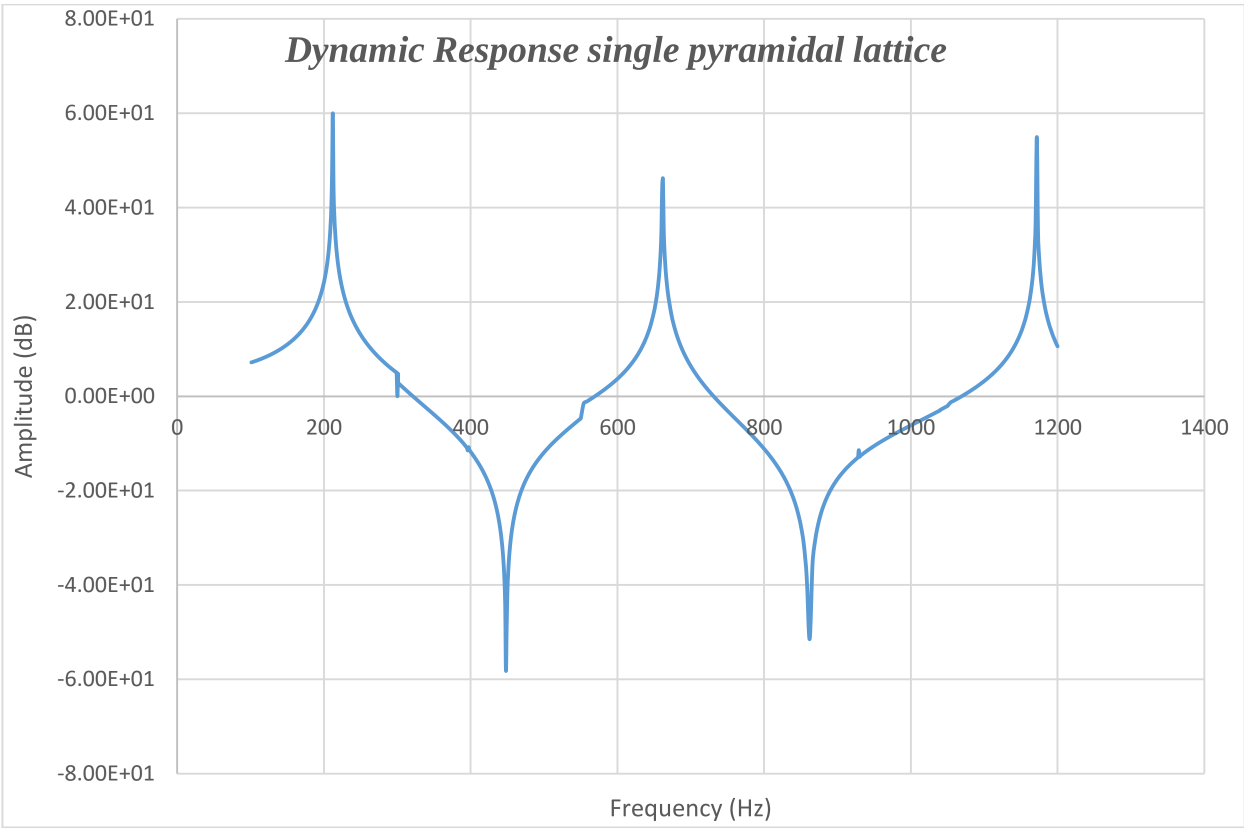


Fig. Dynamic Response single pyramidal lattice

For better understanding we have plotted the deformation data at modes obtained from both structures using harmonic analysis. By plotting the data we have seen that both the structures have similar deformation curve but for double pyramidal structure the deformation is far less than the single pyramidal structure.

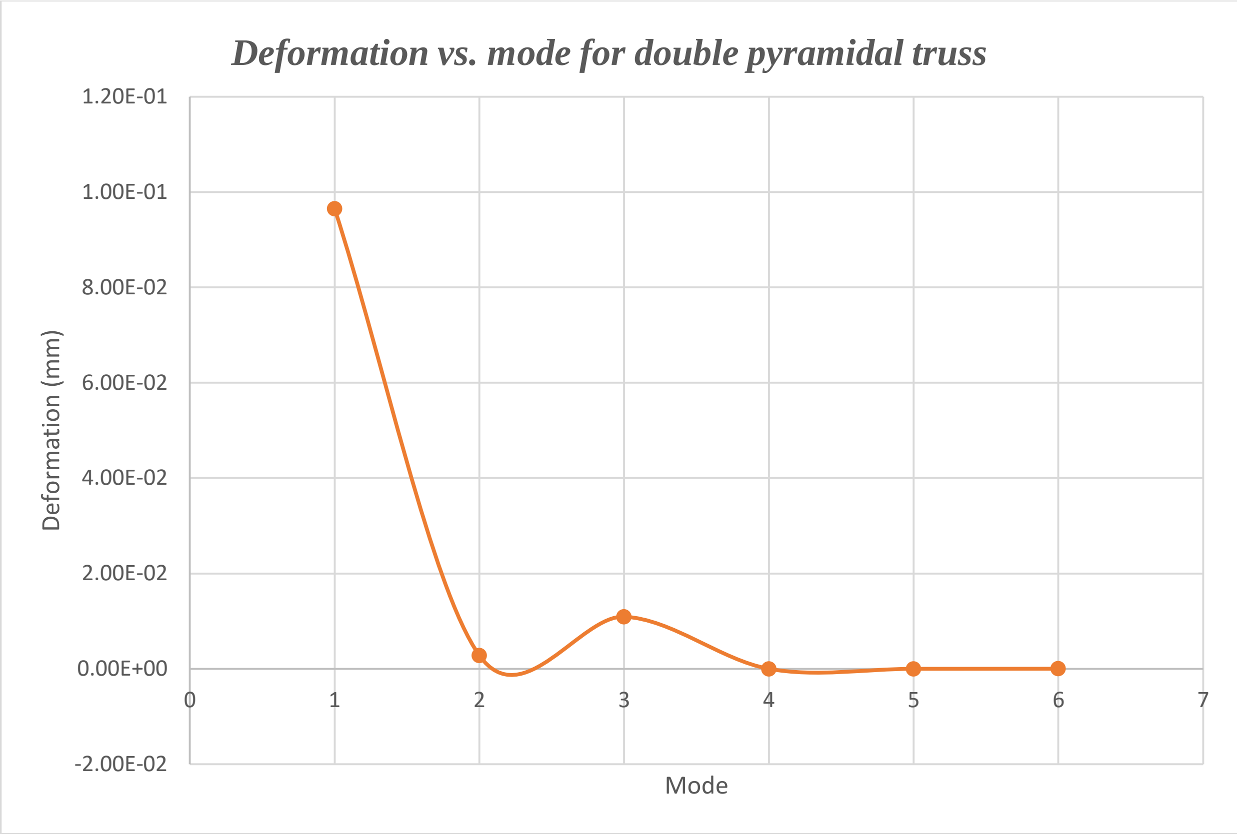


Fig. Deformation vs. mode for double pyramidal truss

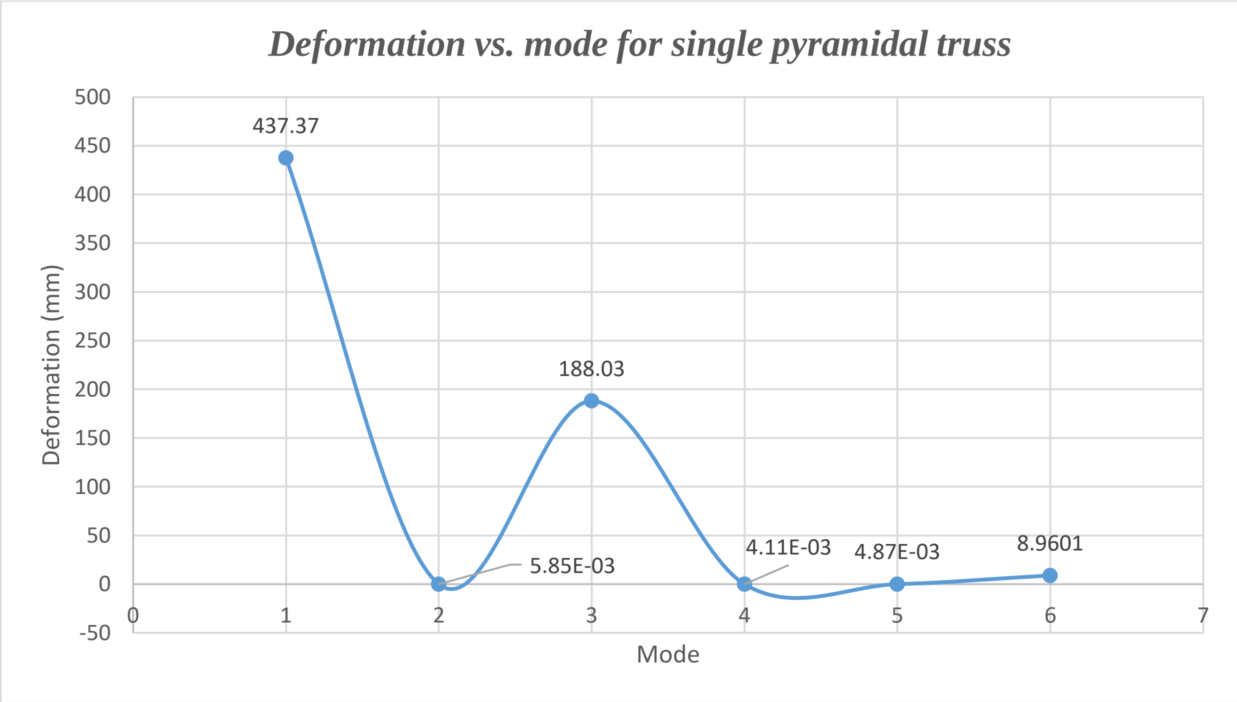


Fig. Deformation vs. mode for single pyramidal truss

5.4 THE INFLUENCE OF FIBER ORIENTATION

According to mechanics of composite materials, the bending– stretching coupling and bending–twisting coupling existing in laminated plates could reduce the load-bearing capacity and natural frequency of structures, a symmetric angle-ply laminated plate consisted of four ±θ ply pairs through the thickness were considered in order to eliminate these effects for the damping properties of hybrid sandwich structures. Natural frequencies for the first five modes for different fiber orientation is shown in the figure below.

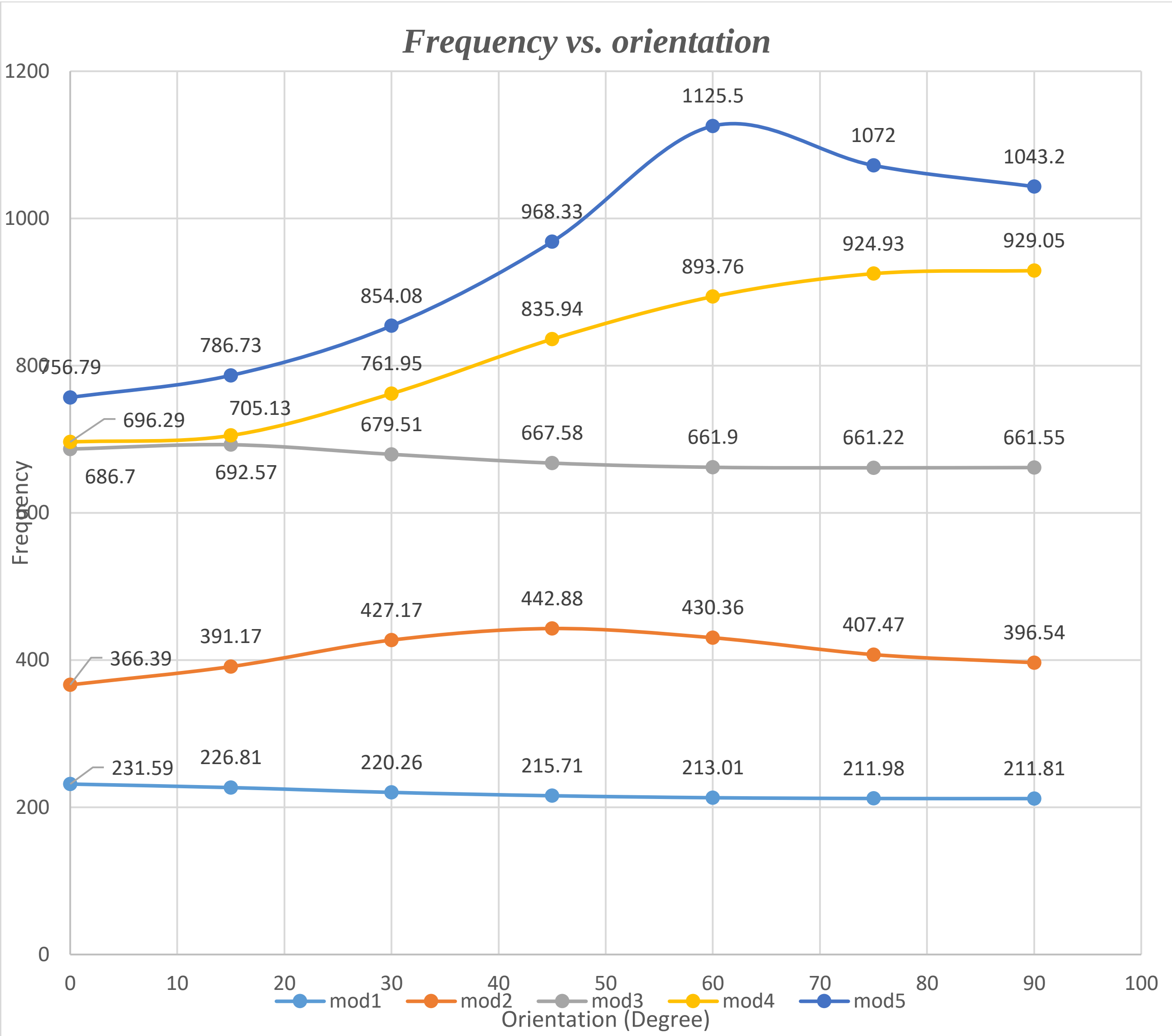


Fig. Frequency vs. orientation

From the above figure we can observe that for the first three modes the natural frequencies are almost constant with the variation of fiber orientation. And for the 4th, 5th and higher modes it gradually increases to a maximum and the starts to decrease.

Chapter Six

Conclusion & Suggestions for further Research

6.1 CONCLUSION

Numerical simulation of methods were carried out to study the vibration performances of hybrid carbon fiber composite pyramidal truss sandwich panels with truss-cores of reciprocal double-pyramidal truss lattice as well as single pyramidal truss lattice. Here we have simulated both structures using both static and dynamic loading. From the results of numerical analysis we can reach to a conclusion that, both structure behave differently in each loading from each other. For static loading, we have seen that single pyramidal structure have better load bearing capacity and lesser deformation. For dynamic loading in harmonic response analysis double pyramidal structure results in lesser deformation and higher load bearing capacity where the deformation of single pyramidal structure increases out of bound. For better and more exact vibration characteristics of both structure experimentation is needed.

6.2 SUGGESTIONS FOR FURTHER RESEARCH

This investigation was done using a very thin carbon fiber laminate and rod. In order to determine its usability and applicability we have to compare it with its metallic counterparts such as aluminum, titanium alloy etc. Moreover the structure was not optimized for length of rod, there distances and dimensions. For getting a better structure, optimization is needed. Since we have compared using only one variation of epoxy carbon fiber composite material, changing of material might result in better performance.

REFERENCES

[1] Jinshui Yang, Jian Xiong, Li Ma, Bing Wang, Guoqi Zhang, Linzhi Wu, 2013. Vibration and damping characteristics of hybrid carbon fiber composite pyramidal truss sandwich panels with viscoelastic layers.

[2] Zhenyu Xue, John W. Hutchinson, 2001. A comparative study of impulse-resistant metal sandwich plates.

[3] Nathan Wicks, John W. Hutchinson, 2000. Optimal truss plate.

[4] S. Rao, 2011. Mechanical Vibration, 5^{th} Ed.

[5] http://mathworld.wolfram.com/HarmonicAnalysis.html

[6] https://en.wikipedia.org/wiki

[7] http://www.ansys.com/products/platform/ANSYS-Meshing