THESIS PAPER
ON

STATIC AND FREE VIBRATION ANALYSIS OF LAMINATED COMPOSITE AND SANDWICH BOX BEAM USING ANSYS

Submitted by

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under the guidance of

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This is to certify that **BANASREE RAY(nee DAS)** (Exam Roll NoM4CIV23014, Registration no70535 of 1998-1999) has carried out the thesis work entitled "**STATIC AND FREE VIBRATION ANALYSIS OF LAMINATED COMPOSITE AND SANDWICH BOX BEAM USING ANSYS"** under my direct supervision & guidance. She carried out this work independently. I hereby recommend that the thesis be accepted in partial fulfillment of the requirements for awarding the degree of "**MASTER OF ENGINEERING IN CIVIL ENGINEERING (STRUCTURAL ENGINEERING**)".

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This foregoing thesis is hereby approved as credible study on an Engineering Subject carried out and presented in a manner satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted.

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DECLARATION

I, Banasree Ray(nee Das) a student of Master of Engineering in Civil Engineering Dept. (Structural Engineering), Jadavpur University, Faculty of Engineering & Technology, hereby declare that the work being presented in the thesis work entitled, **“STATIC AND FREE VIBRATION ANALYSIS OF LAMINATED COMPOSITE AND SANDWICH BOX BEAM USING ANSYS”** is authentic record of work that has been carried out at the Department of Civil Engineering**,** Jadavpur University, under Associate Professor, Dr. Sreyashi Das (nee Pal), Department of Civil Engineering**,** Jadavpur University. The work contained in the thesis has not yet been submitted in part or full to any other university or institution or professional body for award of any degree or diploma or any fellowship.

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CHAPTER 1

Introduction

1.1 Background

Composite laminated materials are widely used in aircraft, marine, automotive, sporting goods, and biomedical industries. The high specific stiffness, high specific strength, and low-density of composites make them suitable for construction of various primary and secondary structures of military and civilian aircrafts. Now-a-days these composites are used extensively in a variety of industrial areas such as box girder bridges, ships, aircraft and offshore oil platforms due to their good corrosive resistance, long fatigue life, good thermal characteristics, ease in fabrication and other significant attributes.

In materials science, a sandwich-structured composite is a special class of composite materials that is fabricated by attaching two thin-but-stiff skins to a lightweight but thick core. The core material is normally low strength, but its higher thickness provides the sandwich composite with high bending stiffness with overall low density.

Box beam structures are thin-walled members with closed cross sections which have been extensively used in a variety of structures that require high strength-to weight and stiffness-to-weight ratios. Some advantages of using box beam structures are as follows:

a. Provides increased torsional stiffness due to hollow rectangular shape. The hollow structure of box beams helps distribute the loads more evenly and reduces deflection.
b. Box beams offer improved resistance to bending due to their geometry. The closed shape of the beam provides a higher moment of inertia, resulting in greater strength and stiffness.
c. Box beams have a sleek and modern appearance due to their clean lines and symmetrical shape. This aesthetic appeal makes them a popular choice in architectural designs where visual appeal is a consideration, such as in exposed structures or interior elements.
d. Box beams can be used in various applications beyond structural support. Their hollow design allows for the integration of utility services, such as electrical wiring, plumbing, or HVAC systems, within the beam itself. This feature enhances space efficiency and simplifies installation, making box beams suitable for applications that require concealed services.
e. While box beams may have higher material costs compared to I-beams, they can offer cost savings in certain scenarios. The increased stiffness and strength of box beams can reduce the need for additional structural elements, such as bracing or secondary support, resulting in potential cost savings in overall construction.

Thin-walled structural shapes made up of composite materials, are being increasingly used in many engineering fields. The main advantage of the use of composite materials in the walls of the beam cross section is the ability to tailor the mechanical properties of the beam to a specific application. These offer many advantages over conventional materials, such as weight reduction and corrosion resistance. The deformation of box-beam is described by extension, bending, twisting, shearing, and torsion related out-of-plane warping. By varying the ply lay-up within the beam walls (fiber orientation angles, stacking sequence, ply material, etc.) structural designers can create elastic couplings between deformations such as extension and torsion, bending torsion, or even bending and shearing of the beam.

In this research, the static and free vibration characteristics of a cantilever box-beam structure have been found out using ANSYS software. Effect of varying the number of layers, fibre angles and core thicknesses for composite sandwich box-beam structures have been studied.

1.2 Overview of Composite Materials

Material systems consisting of two or more phases on a macroscopic scale are regarded as composites. Generally, performance of the composite is much better than its individual components. The stiffer, stronger and discontinuous phase is called reinforcement whereas the less stiff weak phase is called matrix. Another distinct phase existing between reinforcement and matrix as a result of chemical interaction or other processing defects is termed as interphase.

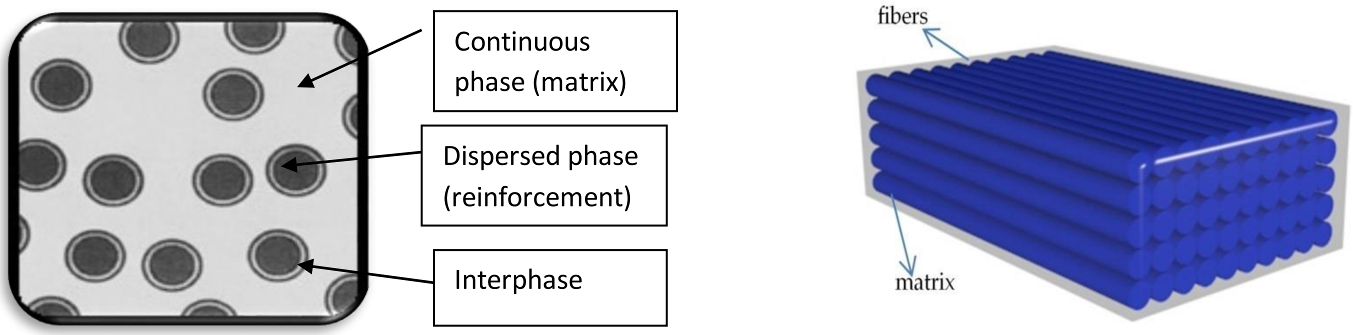


Fig. 1.1 *Diagram showing different phases of Composite material*

The reinforcement of a composite may be in the form of continuous or short fibres, particles of various shapes and whiskers. It contributes to or determines the composite stiffness and strength. Materials possessing high strength, high stiffness and relatively low density are usually preferred as reinforcing materials. The matrix is the main load-bearing constituent governing the mechanical properties of composites. The main role of matrix is to provide protection and support for the sensitive fibres and transfer local stress from one fibre to another.

Composite materials can be broadly classified as fibrous, laminated and particulate depending on the type, geometry and orientation of the reinforcement phase as shown in Fig. 1.2.

Particulate composites consist of particles of various sizes and shapes randomly dispersed within the matrix. Particulate composite consists of metallic or non-metallic particles dispersed in metallic or non-metallic matrices. The continuous fibre composite consisting of long fibres shows better strength and stiffness. In fibrous composite materials, the fibres are embedded in a matrix. Fibre reinforced composites are characterized by the type of matrix used. Polymer matrix composites are primarily suited for low temperature applications. Ceramic and carbon matrix composites are generally suited for high temperature applications.

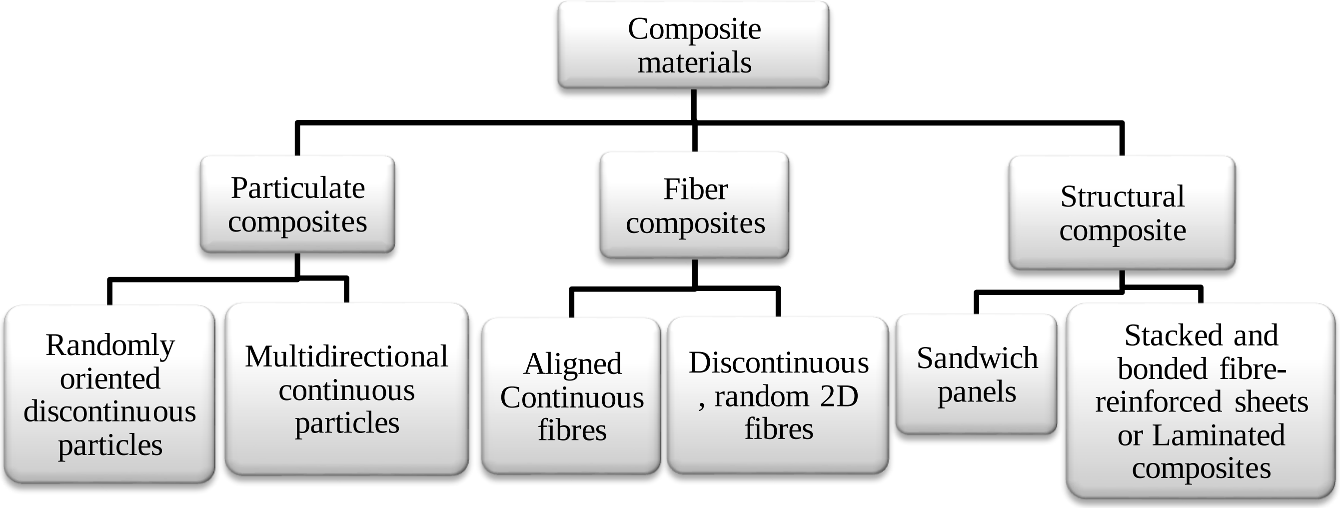


Fig. 1.2 *Classification of composite materials*

In laminated composite plates layers of different properties are bonded together to act as an integral part. A lamina is a plane layer of unidirectional fibres in a matrix. It is an orthotropic material with principal axes in the direction of the fibres. Two or more laminae with different fibre angle orientations are bonded together to form a laminate. A lamina is usually treated as an elastic material having linear stress-strain relationship. Depending on the orientations of fibres of the laminae, a laminate may be symmetric, anti-symmetric or unsymmetric. If the fibre orientations are 0° and 90°, then the laminate is termed as cross-ply for any other sequence it is termed as angle ply.

Matrices are classified broadly based on their composition as polymeric, metallic, ceramic and carbon. The polymeric type may be further subdivided into thermoset and thermoplastics. Thermoset resins are mostly used and some of the common types of thermoset resins are polyesters, epoxies, polymides and vinylesters. These types of matrices are mainly used at lower temperature.

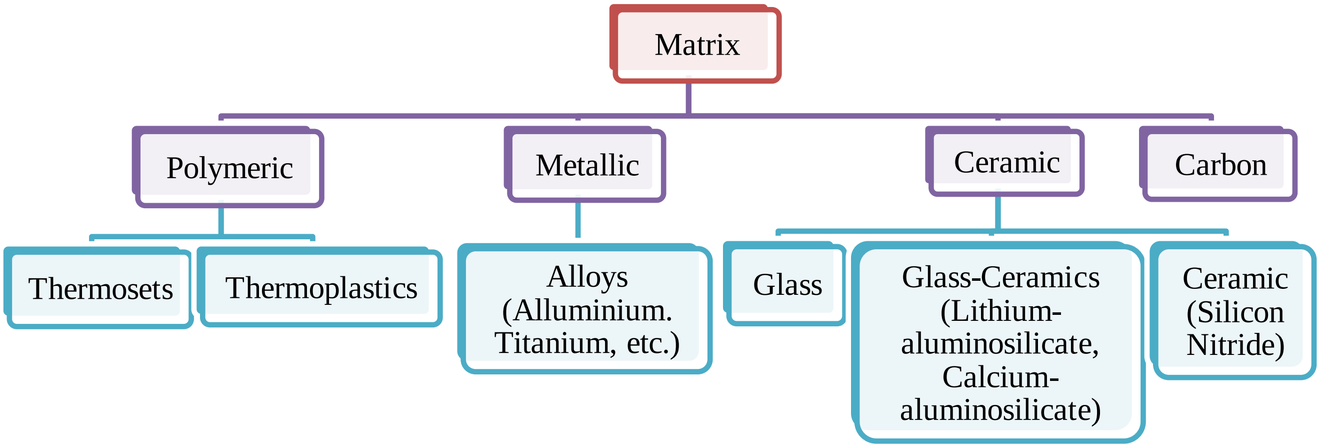


Fig. 1.3: *Classification of matrix of composite materials*

Thermoplastics are fully polymerised polymers and can be altered physically by softening or melting them with heat. They can tolerate more heat compared to thermosets. Metal matrices like aluminium, magnesium and titanium alloys are recommended for high temperature applications up to 800°C. Ceramic and carbon matrices are meant for higher temperature applications exceeding 1000°C. They include glass, glass-ceramic, ceramic and carbon matrices such as lithium aluminosilicate, calcium aluminosilicate, silicon nitride with silicon carbide fibres, etc. Carbon matrices formed by vapour deposition of pyrolitic graphite onto a graphite fibre can be used at temperatures up to 2600° C.

Reinforcement of a composite may be of short or long fibres, particles of various shapes and sizes and whiskers. Amorphous glass fibres are mostly used in low to medium performance composites because of their high tensile strength and low cost. Glass fibres show low stiffness, low fatigue endurance, and rapid property degradation when exposed to severe hygrothermal environment. Carbon fibres manufactured from rayon, polyacrylonitrile or petroleum pitch are mostly used for advanced composites having ultrahigh stiffness and increased thermal conductivity. Kevlar or aramid fibres are organic fibres having very high stiffness. Boron and other ceramic fibres such as silicon carbide and alumina have high stiffness, high use temperature and high strength. The superior performance of composites is attributed to their *high specific strength* and *high specific stiffness*. These two properties are controlled by the fibres.

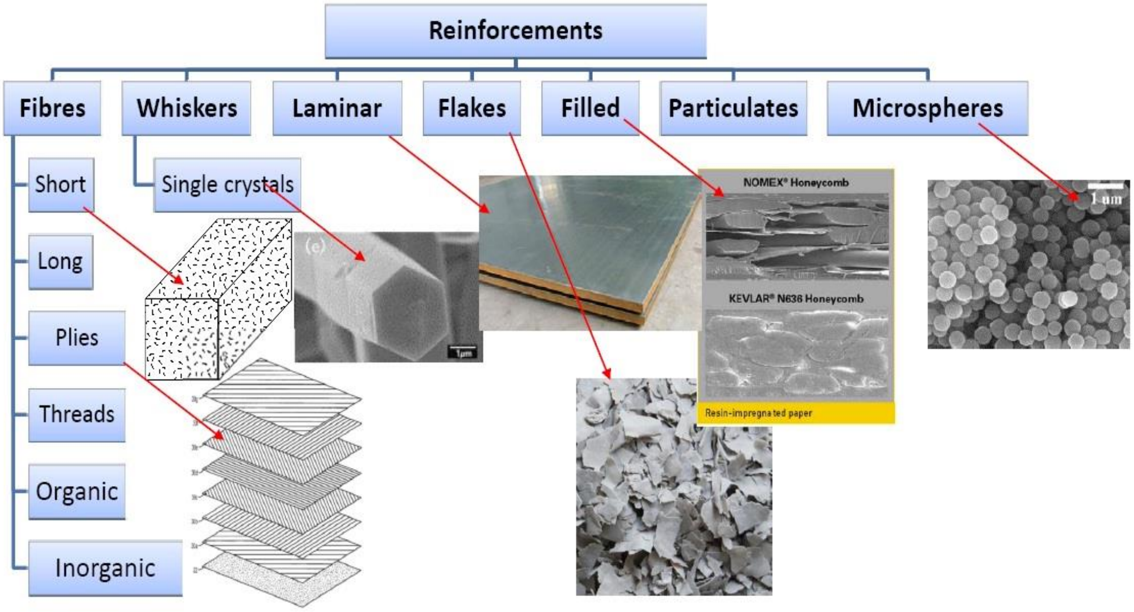


Fig. 1.4: *Classification of fibres of composite materials*

1.2.1 Overview of Sandwich Materials

Sandwich Material has become increasingly popular due to its light weight and high stiffness. A sandwich structure consists of the faces, the core and the adhesive joints.

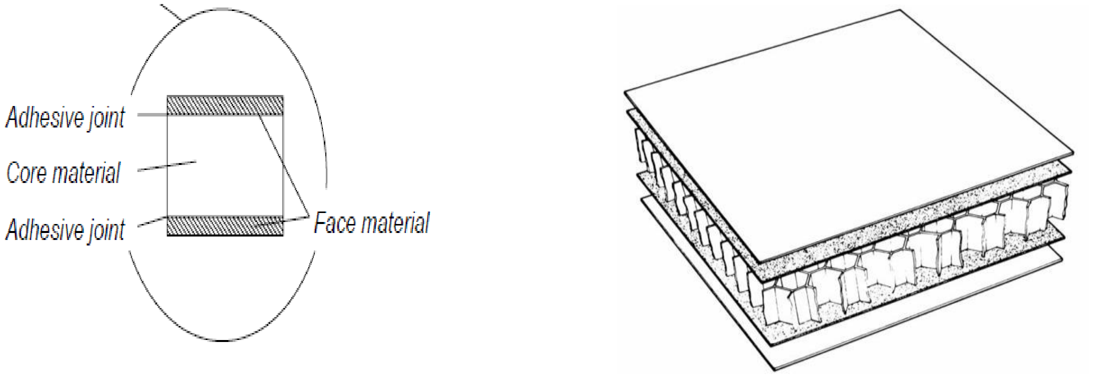


Fig. 1.5: *Sandwich construction with honeycomb core*

The facing skins of a sandwich panel can carry the bending stresses to which the beam is subjected, with one facing skin in compression, the other is in tension. The core (honeycomb) resists the shear loads, increases the stiffness of the structure by holding the facing skins apart, and improving the beam resistance. it gives continuous supports to the facing skins to produce a uniformly stiffened panel. The core-skin adhesive rigidly joins the sandwich components and allows them to act as one unit with a high torsional and bending rigidity.

Face Materials

Any structural material which is available in the form of thin sheet may be used to form the faces of a sandwich panel. The properties of primary interest for the faces are;

- High stiffness giving high flexural rigidity
- High tensile and compressive strength
- Impact resistance
- Surface finish
- Environmental resistance (chemical, UV, heat, etc.)
- Wear resistance

Core Materials

The cores used in load carrying sandwich constructions can be dividedinto four main groups as mentioned below and schematically illustrated in Fig.1.6.

- corrugated
- honeycomb
- balsa wood
- cellular foams

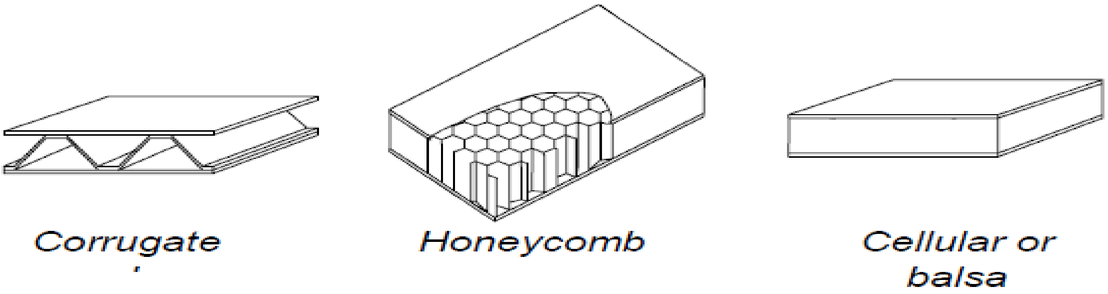


Fig. 1.6: *Different types of cores for sandwich material*

The functions of the sandwich such as thermal and acoustical insulation depend mainly on the core material and its thickness. The primary properties of core materials are

- Low density
- High shear modulus
- High shear strength
- High stiffness perpendicular to the faces
- Thermal insulation

Honeycomb cores: Core materials of honeycomb type have been developed and used primarily in aerospace applications. However, cheap honeycomb materials made from impregnated paper are also used in building applications. Honeycomb materials can be manufactured in a variety of cell shapes but the most commonly used shape is the hexagonal shape. Others are the square, the over-expanded hexagonal or the so-called “flex-core.”

Balsa wood

Balsa was the first material used as cores in load carrying sandwich structures. Balsa is a wood but under a microscope it can be seen as a high-aspect-ratio closed-cell structure. Thefibres or grains are oriented in the direction of growth producing cells with a typical length of0.5-1 mm and with a diameter of about 0.05 mm, thus giving the cell ratio of approximately1:25.

1.3 Applications of Composite and Sandwich Materials

Composite and sandwich materials are now used in a variety of applications ranging from industrial, sports to high performance aerospace components. Fibre reinforced plastics are increasingly used owing to their high specific strength, high specific stiffness and low density. These materials show higher fatigue endurance and good corrosive resistance. Composites can be easily tailored by designers for different applications. Reduction of weight is an important issue in case of aircraft design and thus uses of composites continue to expand in aerospace industry. Composite materials are widely used in aircraft, marine, automotive, sporting goods, and biomedical industries. Some of applications of composites are briefly described below.

- **Aerospace**: Stiffer and lightweight graphite composites are used in the construction of space antennae, mirrors and optical instruments. The lesser values of thermal and hygric expansion coefficients of these materials make them suitable for such uses in severe hygrothermal environment where extreme dimensional stability is required for accurate functioning of these equipments. Carbon fibres are used in extreme temperatures as the heat shielding material of rocket nozzles, re-entry structures and also in jet engines. The lightweight and high rigidity of these materials makes them suitable to be used in rocket motor casings and rocket launchers. Reduction in weight nearly up to 25% can be achieved by using fibre reinforced plastics instead of conventional materials in an aircraft. Graphite-epoxy and boron-epoxy fibres are widely used in aircraft structures. Nearly 50% of the Boeing 787 including the fuselage, fairings, floor beams, wing trailing edge surfaces and empennage are made up of carbon-epoxy and graphite-titanium composites. Advanced composites do not corrode like metals. The combination of corrosion and fatigue cracking is a significant problem for aluminium commercial fuselage structure which is eliminated by the use of composites. The lightweight, damage tolerant and stealth characteristics of composites make them suitable for many military aircrafts. Carbon and Kevlar fibre composites are used in making many unmanned vehicles by NASA. Airbus A380 uses a substantial amount of a hybrid glass/epoxy/aluminium laminate which combines the advantages and mitigates the disadvantages of metals.

- **Transportation**: Composites are widely used for manufacturing automotive parts and automobiles, truck and railway coaches. With increasing number of passengers and stringent rules of safety being laid for comfortable journey of passengers, trains are getting heavy day by day. Thus, to reduce the weight of trains use of composites is becoming necessary. Glass reinforced polymers and sandwich materials are some of the materials used in modern railway coaches. The stiffness and cost effectiveness offered, apart from easy availability of raw materials, make composite materials the obvious choice for applications in surface transportation. In heavy transport vehicles composites are used with cost effectiveness and also for reducing weight. A combination of polyester resin with a variety of reinforcements offers low cost, easily designable production of functional parts of road vehicles.

- **Automotive**: Carbon fibre reinforced epoxies have been used in racing cars and recently for the safety of cars. Thermoplastics are also used in manufacturing vehicle parts. In manufacturing of automobile parts, glass and sisal fibres usually find the maximum use.A reinforced-plastic composite costs more than sheet steel, when considered on the basis of cost and performance but other qualities justify the high expenditure. Mechanical properties of the parts, which affect the thickness and weight offer enough savings to render them more effective than steel. Some complicated parts of light commercial vehicles, which need casting, may be compression moulded from composites of the sheet or bulk variety. State-of-art technologies of moulding, tooling and fabricating have thrown open possibilities of increased manufacturing of vehicles that use reinforced polyesters. Materials used in automotive body parts show high tensile strength and flexural moduli. The material is not ductile and hence will not yield and the failure is accounted only in terms of fracture. These properties and thickness, determine the maximum bending moment which is several times higher than the point of fracture for steel sheets. Composite panels are used as the complete outer skin of the body to give a unique look. Good stability against corrosion or impact makes the composites widely used in vulnerable valance panels below the front and rear bumpers. Signal lamps, indicator lamps of vehicles are fabricated from glass-reinforced composites. For tractors the most crucial parameter is weight reduction as it directly affects efficiency, payload and the economy. Durability is the chief factor as these vehicles are normally realizations of capital investments. Time required, cost and frequency of maintenance add substantially to the total costs. Therefore, it is natural to try and reduce these factors to a minimum. Fibre glass reinforced polyester is widely used in various parts of trucks.

- **Civil/Construction**: Applications of composites range from non-structural gratings and claddings to full structural systems for industrial supports, doors and windows, paneling, furniture, buildings, long span roof structures, tanks, bridge components complete bridge systems and other interiors. Acrylic resin with quartz sand composite is used for manufacturing kitchen sinks. Usage of composites for damage repairing, seismic retrofitting and upgrading of concrete bridges finds increased adoption as a way to extend the service life of existing structures, they are also being considered as an economic solution for new bridge structures. High-performance fibres such as glass, carbon, aramid and hybrids impregnated with resin systems ranging from vinyl esters and other thermosetting resin systems to thermoplastics are used as grid-type reinforcement for concrete structures. Decks for both pedestrian and vehicle bridges across waterways, railways and roadways are now built entirely from composites. The composite deck has six to seven times the load capacity of a reinforced concrete deck with only 20 percent of the weight. Among a wide array of composite products, pultruded profiles such as gratings, ladders, cable trays, solid rods and other sections are used in many structural application with Class I flame retardancy. The Fiber-line Bridge, Kolding, Denmark was designed by the Danish engineering Company, Ramboll using the pultruded profiles. Nowadays, composites are used in peripheral structures of aerodromes. The potential and application of high-performance composites has revolutionized space structural technology. Composites are an attractive proposition considering the embedded energy (energy required to manufacture) especially against steel, aluminium and other metals. Composites are considered an ideal choice for building materials because of their high impact resistance, corrosion resistance, thermal and acoustic insulation. Natural fibre composites are gaining wider acceptance from the point of view of wood substitution.

- **Power**: High voltage electrical transmission towers are now being constructed from pultruded composite sections using a "snap and build" assembly procedure, which eliminates the use of fasteners and adhesives. Composite power and lighting poles are finding increased application for both performance and environmental reasons. Composite modular acoustic enclosures for DG (Diesel Generator) sets are used to control of Noise Pollution. Other potential applications of composites in this sector are third rail covers for underground railway, structures for overhead transmission lines for railway, fibre optic tensile members, switchgear frames, aerial lift-truck booms. Composites made from refractory metals combined with metals are used as electrical contacts and to interrupt very high currents and sustain mechanical action.

- **Marine Application**: Composites are used in high pressure and aggressive environmental situations for applications in oil gas, piping system, topside applications, down-hole tubing in sub-sea, and others. The tailor ability of composites to suit specific applications has been one of its greater advantages such as imparting low thermal conductivity and low coefficient of thermal expansion, high axial strength, and stiffness etc. Due to corrosion resistance, mouldability and maintenance free service of composites they are used in making houseboats. Sandwich composite with PUF foam is used in making hull. Deck portion of the houseboats is composed of moulded resin infused composite gratings supported vertically along the centre line of the hull.

- **Offshore Engineering**: Composites meet diverse design requirements with significant weight savings and exhibit high strength-to-weight ratio compared to conventional materials. Composites have found extensive applications in the oil and gas industry since last two decades. In the offshore oil and gas industry, the cost of manufacturing and erecting oil rigs has reduced significantly by replacing heavy metal pipelines with lighter ones made of composites. Composite pipes are also used for fire water piping, sea water cooling, draining systems and sewerage. The high cost to replace steel piping in retrofit applications and increased longevity in new construction are driving the use of composites, which withstand severe conditions as experienced in offshore environment. Use of composite pipes has reduced problems, like corrosion and blockage of fire lines, reduction in structural support sizes and material handling during construction. Glass Reinforced Epoxy (GRE) piping system is successfully used in offshore environments against highly corrosive fluids at various pressures, temperatures, adverse soil and weather conditions (especially in sea water cooling lines, air vent systems, drilling fluids, firefighting, ballasts and drinking water lines in offshore application, oil exploration, desalination, chemical plants, fire mains, dredging, portable water etc.). Conventionally, grids/gratings are made of mild steel/cast iron. Due to the limitations on corrosion resistance, weight, durability, lifecycle costs etc. for the metallic gratings, composite grids/gratings perform much better due to their superior properties under aggressive environments as in chemical process industry.

- **Bio-medical**: Bio-medical prosthetic devices are artificial replacements that are used in the human body to function as original parts.Composite material has been identified as the new class of synthetic bio-materials. Lightweight carbon-fibre reinforced polymer-matrix containing polysulfone or poly-ether-ketone is used for composite limb. The Mahaveer Vikalang Sahayata Samithi, Jaipur developed an artificial leg made of high-density polyethylene (HDPE) that permits squatting and walking on uneven ground. It is waterproof, simple, durable and lighter in weight and looks like a natural foot. Prosthesis are used to replace not only lost arms and legs, but also bone, artery, heart valve replacements, artificial eyes, teeth, optical lenses and hearing aids.

- **Sports**: For manufacturing sports goods consideration of characteristics like strength, ductility, density, fatigue resistance, toughness modulus, damping coefficient, cost, etc. are required to be considered. To meet the requirements of sports equipment composites is the primary material of choice. Composite materials are used in manufacturing Canoes and Kayaks, Vaulting Pole, Golf and Polo rods, tennis rackets, skis, Archery equipment, Javelin, Hand gliders, Wind surfer boards, Protective sportswear. Carbon composite bike frame is a complex structure with performance characteristics that include lightness, rigidity, durability, shock absorption etc. Hybrid fibre (carbon and aramid), carbon/kevlar epoxy materials are ideal composite materials for bicycle components. The composites are finding application in bicycle components such as Forks, Handle bars and Connecting bar ends, Seat posts, etc. Radius Engineering- Salt Lake City, Utah developed Swix carbon fibre ski poles which have been used by gold medal Olympic skiers since 1990s. Radius developed the Trek carbon fibre bicycle frame which is much lighter than the corresponding steel frame.

1.4 Comparison table for Common material, Composite material and Sandwich material

Conventional material	Composite material	Sandwich material
Common or isotropic material consists of one type of material i.e., modulus of elasticity, Poisson's ratio and density of whole structure are same.	A composite material consists of two or more constituent materials combined in such a way that the resulting material has more useful applications than the constituent materials alone.	A sandwich material consists of a pair of thin stiff, strong skin and a thick lightweight core to separate the skins and carry the loads from one skin to the other and an adhesive attachment which is capable of transmitting shear and axial loads to and from the core.
Low strength and stiffness-to-weight ratio	High strength and stiffness-to-weight ratio	High ratio of bending stiffness to weight as compared to monolithic construction.
High weight	Low weight	Very low weight
Fatigue resistance less than composite and sandwich material.	Excellent fatigue resistance	High resistance to mechanical and sonic fatigue
Less corrosion resistance	Excellent corrosion resistance	Excellent corrosion resistance
Less damping characteristic	Good damping characteristic	Good damping characteristic
Less thermal insulation	Improved thermal insulation	Improved thermal insulation
It is use in beam, column, building structure, bridge, canal, tunnel etc.	Application of composites in almost every aerospace structure, ships, tanks, and marine structures. On civilian side one finds use of composites in bridges, sporting goods, repair of existing steel and concrete structures, enhancing earthquake resistance of existing structures, etc.	Sandwich construction has found extensive application in aircraft, missile and spacecraft structures due to high strength to weight ratio. This type of construction consists of thin, stiff and strong sheets of metallic or fiber composite material separated by a thick layer of low-density material.

1.5 Objective of present study

In this research static and free vibration analysis of laminated composite and sandwich box beam structures have been performed using finite element software ANSYS. The effect of variation of fibre angle, number of composite layers, skin and core thicknesses on the static deflection and natural frequencies have been studied.

1.6 Scope of present study

- Static and free vibration analysis of laminated composite and sandwich cantilever box beam structures have been performed**.**
- The box beam structure is modelled using ANSYS plate element SHELL 281.
- ANSYS software used first order shear deformation theory.
- Eight noded isoparametric plate bending element has been used.

CHAPTER 2

Literature Review

2.1 Historical development of composite material box beam

Rectangular thin-walled beams, also known as ‘‘thin-walled box beams”, have a mature technical system. Herakovich [1] introduced stress calculation method of composite laminated plate and derived strength checking method for laminated plate thin-walled box beam. The theory of thin-walled closed-section members made of isotropic materials was first developed by Vlasov [2] and Gjelsvik [3].
Chandra et al. [4] presented a theoretical-cum-experimental study of free vibration characteristics of thin-walled composite box beams with bending-twist and extension-twist coupling under rotating conditions. Song and Librescu [5] focused on the formulation of the dynamic problem of laminated composite thick and thin-walled, single-cell beams of arbitrary cross-section. Armanios and Badir [6] derived the equations of motion for free vibration analysis of anisotropic thin walled closed-section beams using a variational asymptotic approach and Hamilton's principle. The analysis is applied for two kinds of laminated composites: the circumferentially uniform stiffness (CUS) and the circumferentially asymmetric stiffness (CAS). Dancila and Armanios [7] used the governing equations provided by Armanios and Badirto isolate the influence of coupling on free vibration of closed-section beams exhibiting extension-twist, bending-twist coupling. Qin and Librescu [8] incorporated non-classical effects such as transverse shear and non-uniformity of membrane shear stiffness in anisotropic thin-walled beams. The solution methodology is based on the Extended Galerkin's Method and the non-classical effects on the static responses and natural frequencies are investigated. Recently, Cortinezand Piovan [9] presented the stability analysis of composite thin-walled beams with open or closed cross sections. This model is based on the use of the Hellinger–Reissner principle, that considers shear flexibility in a full form, general cross-section shapes and symmetric balanced or especially orthotropic laminates.

Lee and Kim [10] and Vo and Lee [11] performed the dynamic behavior of a thin-walled composite box beam with doubly symmetric section. This model accounts for the coupling of flexural and torsional modes for arbitrary laminate stacking sequence configuration, i.e., unsymmetric as well as symmetric, and various boundary conditions. A displacement-based one-dimensional finite element model is developed to predict natural frequencies and corresponding vibration modes for a thin-walled composite beam. Tarjan et al.[12] summarized the buckling load estimation methods and provided the corresponding empirical formulas for laminated plate beams under different boundary conditions and load distributions.

Montagnier and Bovet [13] considered critical load failure condition and used analytical mass equation to minimize the number of plies in wing box. Alsahlani et al.[14] combined the theory of Herakovich and Tarjan and proposed a low-order estimation method for thin-walled box beam of solar drones. This method quickly optimized the composite layer of laminated plate box beam and minimized the weight of the structure. Cao and Ou [15] analyzed the strength, rigidity, and stability of a thin walled box beam under various loading and reinforcement conditions by using Finite Element Method (FEM). Further, they analyzed the main mechanical characteristics of the thin-walled box beam.

All the above studies discussed the applicability of laminated composite box beam. However, compared to conventional aircraft, the wing load of solar drone is generally low, and the wall thickness of the box beam designed to meet the strength and stiffness constraints is usually small, which makes structural buckling an important factor to be considered. It has been reported that sandwich structure can provide significant improvement in structural stability with less weight cost than laminated structure, such as the honeycomb sandwich structure, which has been widely used in conventional aircrafts.

Xu et al. [16] investigated the sandwich structure by FEM, and found that the carbon fiber reinforced triangular grid was much stiffer than the honeycomb structure. Rahmani et al.[17] and Boussoula et al. [18] carried out bending analysis of sandwich plates based on the high-order deformation theory with only four unknowns in the displacement field, which made the analysis model simpler to use. Irfan and Siddiqui et al. [19] summarized the recent research progress on the finite element formulation of sandwich plates and analyzed the buckling phenomenon. Chikretal. [20] and Refrafi et al. [21] studied the buckling response of sandwich plates based on the new shear deformation theory, which guarantees the accuracy of the predicted results without using any shear correction factors. Based on this, the effects of geometric and environmental parameters on the buckling response are studied. In terms of design process, multi-stage optimization is widely used in composite structure design.

Zang, et al. [22] studied the stress and strain distribution numerically in the thickness direction in the central region of symmetric composite laminates under uniaxial extension and in-plane pure shear loading. Anido, et al. [23] carried out an experimental evaluation of stiffness of laminated composite rectangular beam under flexure. Three point bending tests were performed on lay-up angle ply $[\pm 45]_s$ beam elements made of AS-4/3501-6 carbon-epoxy. Aktas [24] introduced a deflection function of an orthotropic cantilever beam subjected to point and distributed load using anisotropic elasticity. The deflections at the free end of the beam were calculated numerically using the obtained formulations for different fiber directions. It was found that the free end deflection of the beam increased for angles ranging from 0° to 90° for both load cases due to decreasing of stiffness. Song, et al. [25] presented analytical solutions for the static response of anisotropic composite I beams loaded at their free-end, also the variation of the displacement quantities along the beam span was presented. The solution includes the structural characteristics which are often ignored in the most published studies such as axial and bending stiffness.

A study on Dynamic dispersion curves for non-homogeneous, anisotropic beams with cross section of arbitrary geometry was done by Volvoi V.V et al. [26]. In this paper a code was developed to calculate the dispersion as well as the corresponding mode shapes. The code was based on finite element discretion over the cross sectional domain. With advances in researches a lot of progress was made in analysing the vibrations of beams. In one of the research works by Gavali A.L[27] he studied vibration analysis of beam by numerical discretisation scheme such as finite element method, the differential quadrature method (DQM) etc. A study of Free Vibration Analysis of circular plates with holes and cut outs was done by Thakare S.B et al. [28] In this study an experimental method to determine the modal characteristics of a plate with multiple holes and slots are used which is verified by the finite element analysis (FEA) and ANSYS. Also, the relationship between parameter variations and vibration modes is investigated. These results can be used as guidance for the modal analysis and damage detection of a circular plate with hole. Research was done by Raj R. and Sinha P.K [29] in which they studied the modelling simulation and analysis of cantilever beams of different materials by finite element method analysis and MATLAB programming.

Later, certain specific study was made on cantilever beam by Chaphalkar S.P et al, [30] where modal analysis of cantilever beam structure using finite element analysis and experimental analysis was studied. A study on modal analysis of beam structures was done by Kumar P. et al. [31] where they studied three types of beams namely cantilever, simply supported and fixed beam and obtained their mode shapes and natural frequencies. Research on Free vibration analysis of eccentric and concentric isotropic stiffened plate using ANSYS was done by Siddiqui H.R and Shivhare V [32]. In that paper free vibrations analysis of eccentric and concentric stiffened isotropic plates with central stiffener and double stiffener has been studied and effect of various parameters such as boundary condition aspect ratio of non – dimensional frequency parameters of plates are investigated. A study of free vibration of fixed free beam with theoretical and numerical approach was done by Chopade J.P. et al. [33] Their paper mainly focuses on the theoretical analysis of transverse vibration of fixed free beam and investigates the mode shape frequency.

Further research was carried one of which includes Numerical Investigation of Natural Frequencies for Clamped Longitudinal Composite Plates by Firas T. Al- Maliky [34] in which two finite element model was performed. The fibre and matrix represented as two different materials in the first plate, while the second showed a composite plate. The numerical equations that performed from this study used to investigate the natural frequencies for longitudinal clamped composite plates. A study on modal analysis of central crack stainless steel plate using ANSYS was done by Maliky F.T. Al.- et al. [35]. The purpose of their research was to detect the cracks in stainless steel plates. The modal analysis of free vibration on central crack plate was done. The finite element analysis was performed in ANSYS 18.2 program workbench. The final mesh was generated in square plate with total number of nodes and elements. The prediction in cracks of stainless-steel plates was done by studying the various in dynamic response of structures which provided a benefit method to investigate central cracks in stainless steel plates.

CHAPTER 3

THEORETICAL FORMULATION

In this research the static and free vibration analysis of composite sandwich box beam has been performed using ANSYS student version. Both beam model and plate model has been used in the analysis. The details of beam and shell models are given below [36].

3.1 BEAM188 Element Description

BEAM188 is suitable for analyzing slender to moderately stubby/thick beam structures. The element is based on Timoshenko beam theory which includes shear-deformation effects. The element provides options for unrestrained warping and restrained warping of cross-sections.

The element is a linear, quadratic, or cubic two-node beam element in 3-D. BEAM188 has six or seven degrees of freedom at each node. These include translations in the x, y, and z directions and rotations about the x, y, and z directions. A seventh degree of freedom (warping magnitude) is optional. This element is well-suited for linear, large rotation, and/or large strain nonlinear applications.

The element includes stress stiffness terms, by default, in any analysis with large deflection. The provided stress-stiffness terms enable the elements to analyze flexural, lateral, and torsional stability problems (using eigenvalue buckling, or collapse studies with arc length methods or nonlinear stabilization).

Elasticity, plasticity, creep and other nonlinear material models are supported. A cross-section associated with this element type can be a built-up section referencing more than one material. Added mass, hydrodynamic added mass and loading, and buoyant loading are available.

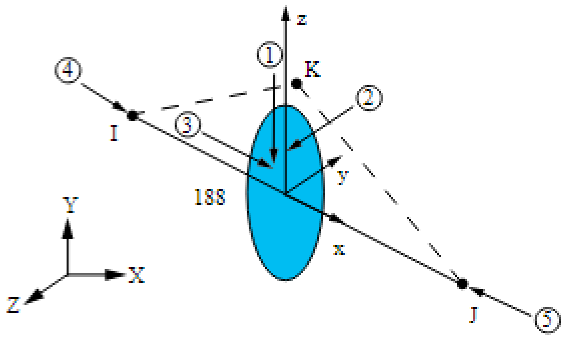


Figure 3.1: *BEAM188 Geometry*

BEAM188 is based on Timoshenko beam theory, which is a first-order shear-deformation theory: transverse-shear strain is constant through the cross-section (that is, cross-sections remain plane and undistorted after deformation).

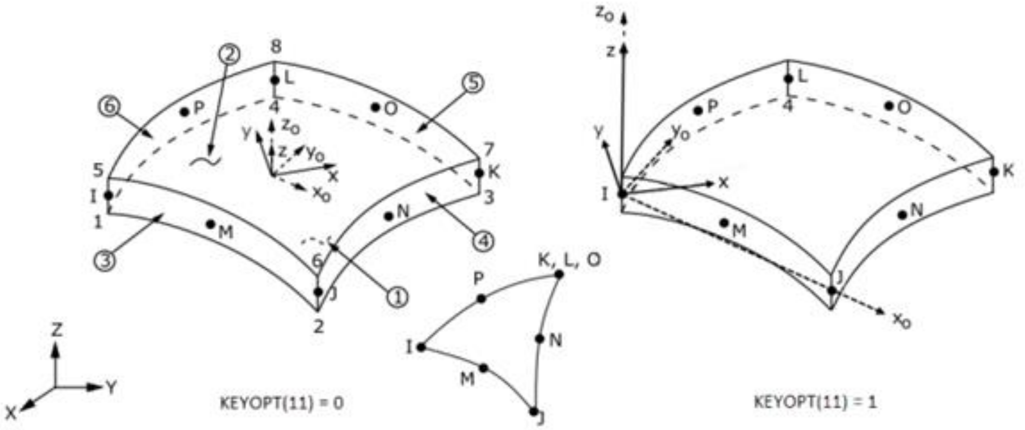
The element can be used for slender or stout beams. Due to the limitations of first-order shear-deformation theory, slender to moderately thick beams can be analyzed. Use the slenderness ratio of a beam structure (GAL^2 / (EI)) to judge the applicability of the element,

3.2 SHELL281

SHELL281 is suitable for analyzing thin to moderately-thick shell structures. The element has eight nodes with six degrees of freedom at each node: translations in the x, y, and z axes, and rotations about the x, y, and z-axes(When using the membrane option, the element has translational degrees of freedom only).

SHELL281 is well-suited for linear, large rotation, and/or large strain nonlinear applications. Change in shell thickness is accounted for in nonlinear analyses. The element accounts for follower (load stiffness) effects of distributed pressures.SHELL281 may be used for layered applications for modelling composite shells or sandwich construction. The accuracy in modelling composite shells is governed by the first-order shear-deformation theory (usually referred to as Mindlin-Reissner shell theory).

The element formulation is based on logarithmic strain and true stress measures. The element kinematics allow for finite membrane strains (stretching). However, the curvature changes within a time increment are assumed to be small.



x_0 = Element x axis if element orientation (**ESYS**) is not specified.

x = Element x axis if element orientation is specified.

Fig. 3.2 *Shell 281 Geometry*

CHAPTER 4

NUMERICAL RESULT

4.1 Validation study

Validation studies are made to test the accuracy of the computer program and the results are compared with those available in the literature. The cases are as follows:

Problem:

A cantilever hollow beam of length L=100 mm and cross-sectional area as shown in Fig 4.1is considered. The beam is subjected to a concentrated load of 1000 N at the free end. The material properties are used: E= 200GPa, γ = 0.3, $\rho = 7850\ Kg/m^3$. The free end deflection and natural frequency is calculated analytically and compared with values obtained analytically and numerically using ANSYS (2022 R2 Student version) taking beam model and plate model respectively. In the beam model, the element taken is BEAM 188 and the load is applied at the free end whereas in the plate model, the element taken is SHELL 281 and the load is applied at the corner nodes only.

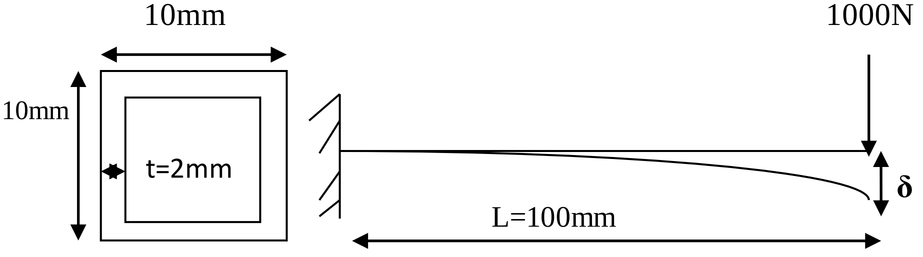


Fig4.1: Geometry of box beam

1. **Static analysis**

The deflection at the end of the above thin-walled composite cantilever box beam are given in Table 1. Theoretical calculation is given in 4.2.

Table 1: Theoretical Deflection at the free end of cantilever box beam

Theoretically	ANSYS (Beam Model)	ANSYS (shell model)
2.298mm	2.338mm	2.448 mm

Here we see that the theoretical deflection of the above beam is less than ANSYS (Beam Model)and ANSYS (Shell Model). So, stiffness of the beam is more in theoretical analysis than ANSYS (Beam Model) and ANSYS (Shell Model).

2. Modal Analysis

The frequency calculation of the above thin-walled composite cantilever box beam are given in Table 2. Theoretical calculation is given in section 4.2.

Table 2: Theoretical Frequency at the free end of cantilever box beam

Theoretically	ANSYS (Beam Model)	ANSYS (shell model)
9.5079 x 10 $^{-4}$Hz	9.36 x 10 $^{-4}$ Hz	9.1655 x 10 $^{-4}$ Hz

Here we can observe that the theoretical frequency of the above beam is more than ANSYS (Beam model) and ANSYS (Shell Model). So, stiffness of the beam is more in theoretical analysis than ANSYS (Beam Model) and ANSYS (Shell Model). Also, it is observed that both for static and free vibration analysis, ANSYS beam model makes the box beam structure stiffer than ANSYS plate model.

4.2 Theoretical calculation

E= 200GPa, $\rho = 7850\ Kg/m^3$

$$I=\frac{1}{12}\{(10)(10)^3 - (6)(6)^3\} = 725.33mm^4$$

Static analysis

$$\delta_{\max} = \frac{Pl^3}{3EI} = \frac{10(10)^3(100)^3}{3\text{x}2\text{x}(10)^5\text{x}725.33} = 2.298\ mm$$

Modal Analysis

$$\text{Frequency}=f = \frac{1.875^2}{l^2\text{x}2\text{x}\pi}\sqrt{\frac{EI}{\rho A}} = \frac{1.875^2}{100^2 x 2 x \Pi}\sqrt{\frac{2x10^5x725.33}{7850x(10^2-6^2)}} = 9.5079\text{x}10^{-4}\text{Hz}$$

4.3 STATIC ANALYSIS

4.3.1. Case Study 1: EFFECT OF NUMBER OF LAYERS ON DEFLECTION OF CANTILEVER BEAM

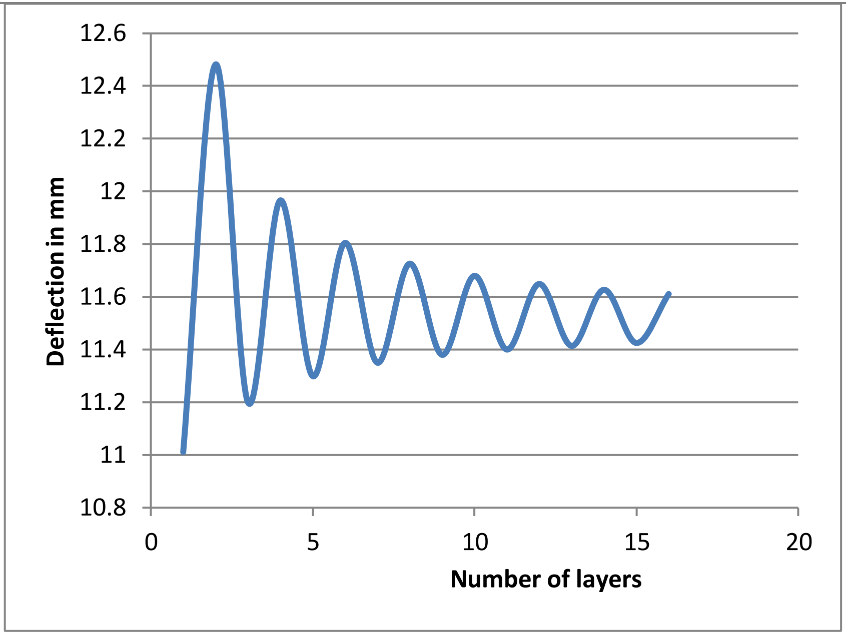
A cantilever box beam of length L=100 mm and cross-sectional area as shown in Fig. 4.2 is considered. The beam is subjected to a concentrated load of 1000 N at the free end. Laminated E-glass Epoxy composite materials with following properties have been used in the study.

$E_1 = 60.7\text{x}10^9 \text{Nm}^{-2}$, $E_2 = 24.8\text{x}10^{9}\text{Nm}^{-2}$, $G_1 = G_2 = G_3 = 12\text{x}10^{9}\text{Nm}^{-2}$ and $\gamma_1 = \gamma_2 = \gamma_3 = 0.23$,

Anti-symmetric cross ply with increasing number of layers (up to 16 layers) have been used. The Deflection at free end of box beam subjected to concentrated load for different cross ply is given in Table 3 in tabular format and a graph of deflection vs no. of layer is also provided.

Table 3: Deflection at Free End of Box Beam Subjected to ConcentratedLoad

DEFLECTION AT FREE END OF BOX BEAM SUBJECTED TO CONCENTRATED LOAD

Plate orientation	Layer	Deflection in mm	
0	1	11.011	
0/90	2	12.482	
0/90/0	3	11.2	
$(0/90)_2$	4	11.966	
$0/90/\bar{0}$	5	11.299	
$(0/90)_3$	6	11.805	
$(0/90/0/\overline{90})_S$	7	11.35	
$(0/90)_4$	8	11.726	
$(0/90)_2\bar{0}$	9	11.38	
$(0/90)_5$	10	11.68	
$(0/90/0)_2\overline{90}$	11	11.4	
$(0/90)_6$	12	11.649	
$(0/90)_3\bar{0}$	13	11.414	
$(0/90)_7$	14	11.627	
$(0/90/0)_3\overline{90}$	15	11.425	
$(0/90)_8$	16	11.611	

Here it is observed that undulation of the graph (deflection versus number of layers) decreases steadily with the increase of number of layers. Also, it is observed that the behaviour is different for odd and even number of layers which is clearly visible from Table 4 and 5. Table 4 shows an increase in deflection value up to 11.45mm when the curve becomes nearly flat. When the number of layers is even, the deflection value reduces exponentially till reaching a constant value of 11.6mm. This indicates that when the number of layers is odd, its stiffness is more than when the number of layers is even.

Table 4: Extracted result from Table 3 (Effect of **odd number of layers** on deflection of Cantilever beam)

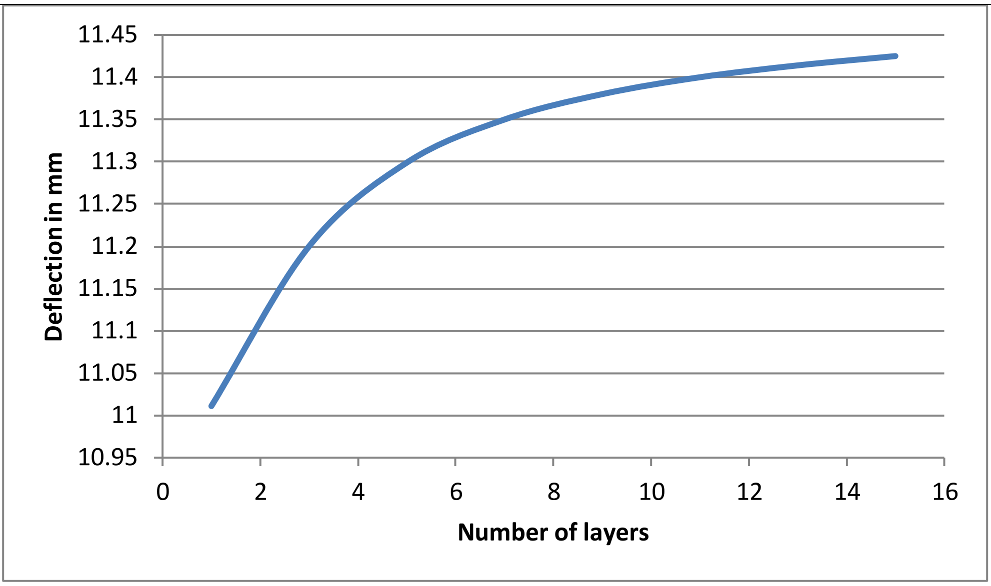
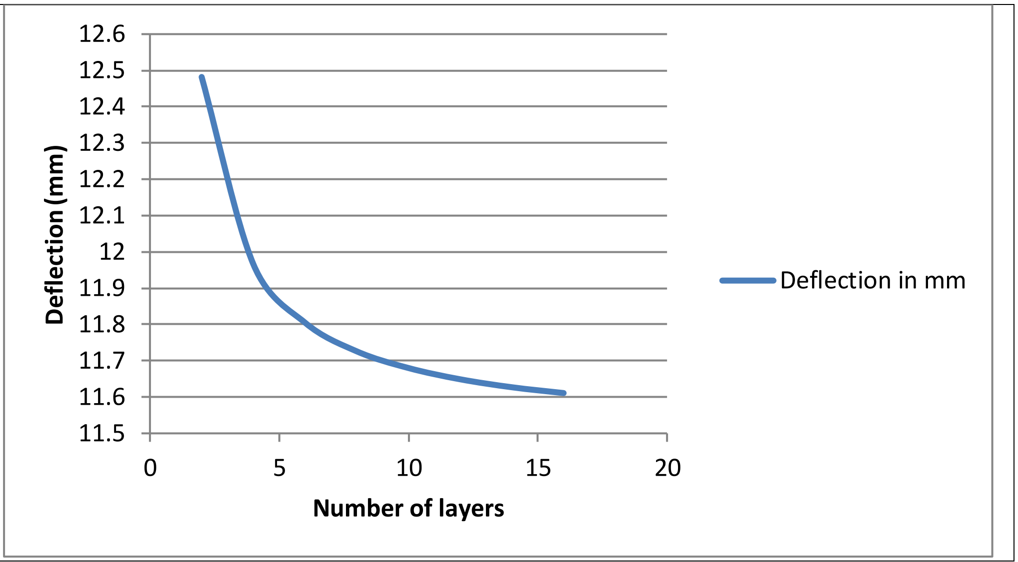
Odd Layer	Deflection in mm	
1	11.011	
3	11.2	
5	11.299	
7	11.35	
9	11.38	
11	11.4	
13	11.414	
15	11.425	

Table 5: Extracted result from Table 3 (Effect of even layers on deflection of cantilever beam)

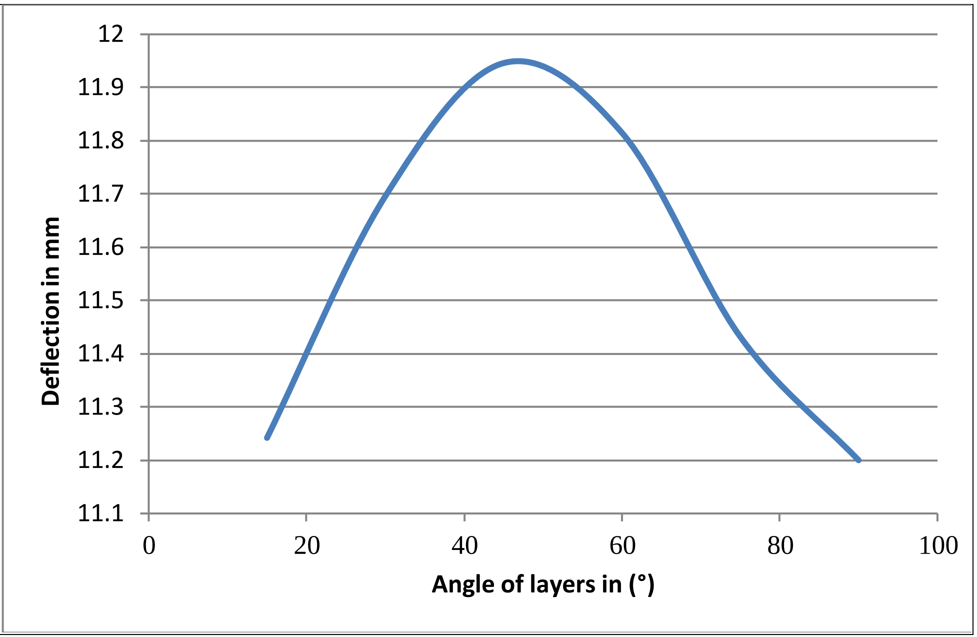
Even Layer	Deflection in mm	
2	12.482	
4	11.966	
6	11.805	
8	11.726	
10	11.68	
12	11.649	
14	11.627	
16	11.611	

4.3.2. Case Study 2: EFFECT OF FIBRE ANGLE ON DEFLECTION OF CANTILEVER BEAM

The beam with same geometry and material properties as used in previous study has been used. The deflection at free end of the box beam has been tabulated in Table 6. The lay up sequence taken is 0/θ/0 where θ has been varied from 15^o to 90^o. Also, a graph is plotted to show the nature of change. It is observed that maximum tip deflection is 11.946mm for 0/45/0.

Table 6 : Tip deflection(mm) with change in fibre angle

Angle of Layer 0/θ/0	Deflection in mm
15°	11.242
30°	11.696
45°	11.946
60°	11.815
75°	11.432
90°	11.2



4.3.3. Case Study 3: EFFECT OF CORE THICKNESS FOR SANDWICH MATERIAL ON DEFLECTION OF CANTILEVER BEAM

Here the geometry of the beam kept same as in Fig. 4.2. Sandwich material properties are used where the core (*c*) material properties are related to composite material properties (f) as follows:-
$E_{2f}/E_{1c} = E_{2f}/G_{1c} = 27.7$, $\gamma_c = 0.35$

The deflection at free end of box beam for different Core thicknesses keeping overall thickness same at 2 mm is given in Table 7 along with a graph.

It is observed that the deflection increases with the increase of core thickness of sandwich layer. Generally softer material is used as core material. Keeping the total thickness same, as the thickness of core material increases, the stiffness of structure decreases and deflection increases.

Table 7: The deflection at free end of box beam using sandwich material subjected to concentrated load

Angle of Layer	Skin Thickness in mm Total thickness t=2mm	Core Thickness in mm Total thickness t=2mm	Deflection in mm
$0/90/\bar{0}$	0.75	0.5	15.160
$0/90/\bar{0}$	0.625	0.75	18.032
$0/90/\bar{0}$	0.5	1	22.269
$0/90/\bar{0}$	0.375	1.25	29.160
$0/90/\bar{0}$	0.25	1.5	42.367

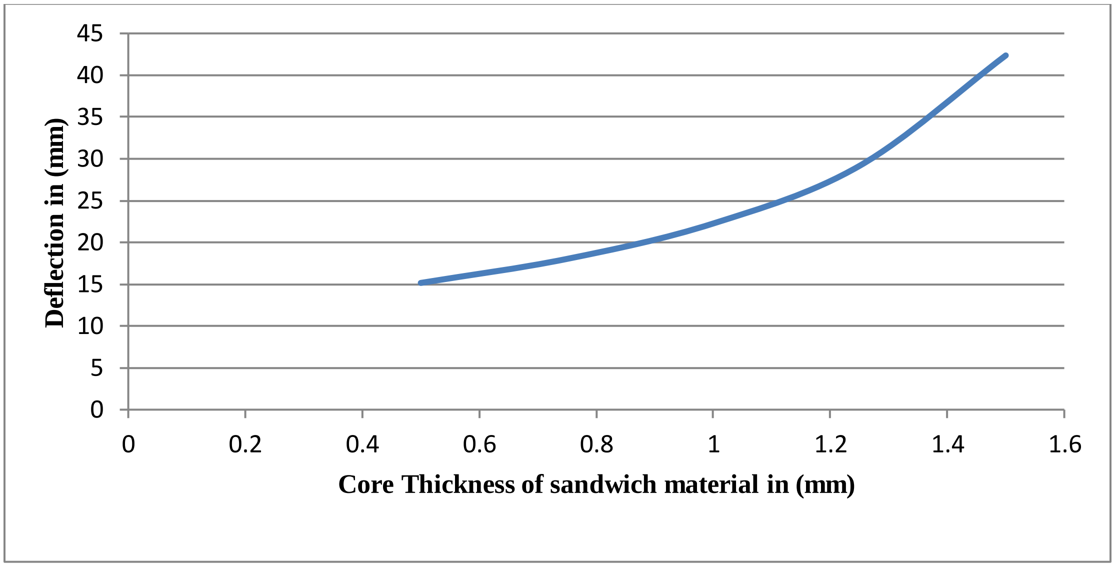


Fig 4.2: Effect of change in core thickness on deflection

4.4 MODAL ANALYSIS

4.4.1. Case Study 1: EFFECT OF NUMBER OF LAYERS ON FREQUENCIES OF CANTILEVER BOX BEAM

The same beam as used in static analysis in section 4.3 has been used for modal analysis. Table 8 shows the effect of number of layers on first five natural frequencies of box beam structure. In Fig. 4.3 the variation of fundamental frequency has been plotted for increase in number of layers. It is observed that the fundamental frequency increases between 1st and 2nd layer then undulation of the graph decreases steadily with the increase of number of layers. Hence this can be said that the effect of increasing number of layers exists for first few layers. With increase in number of layers, the natural frequency tends to get a constant value.

Table 8: Variation of Frequency for different number of layers

FREQUENCY ANALYSIS						
Plate orientation	Layer	Frequency in Hz 1st mode	Frequency in Hz 2nd mode	Frequency in Hz 3rd mode	Frequency in Hz 4th mode	Frequency in Hz 5th mode
0	1	0.85986E-03	0.93543E-03	0.49504E-02	0.53024E-02	0.67642E-02
0/90	2	0.99436E-03	0.99436E-03	0.55608E-02	0.55608E-02	0.67659E-02
0/90/0	3	0.97895E-03	0.10138E-02	0.55226E-02	0.56844E-02	0.67639E-02
$(0/90)_2$	4	0.10151E-02	0.10151E-02	0.56766E-02	0.56766E-02	0.67649E-02
$(0/90/\overline{0})s$	5	0.10019E-02	0.10235E-02	0.56314E-02	0.57315E-02	0.67636E-02
$(0/90)_3$	6	0.10219E-02	0.10219E-02	0.57144E-02	0.57144E-02	0.67655E-02
$0/90/0/\overline{90})s$	7	0.10116E-02	0.10272E-02	0.56771E-02	0.57494E-02	0.67643E-02
$(0/90)_4$	8	0.10253E-02	0.10253E-02	0.57331E-02	0.57331E-02	0.67658E-02
$(0/90)_2\overline{0}$	9	0.10169E-02	0.10292E-02	0.57023E-02	0.57587E-02	0.67648E-02
$(0/90)_5$	10	0.10273E-02	0.10273E-02	0.57443E-02	0.57443E-02	0.67659E-02
$(0/90/0)_2\overline{90}$	11	0.10203E-02	0.10304E-02	0.57181E-02	0.57645E-02	0.67651E-02
$(0/90)_6$	12	0.10287E-02	0.10287E-02	0.57517E-02	0.57517E-02	0.67660E-02
$(0/90)_3\overline{0}$	13	0.10226E-02	0.10312E-02	0.57291E-02	0.57684E-02	0.67652E-02
$(0/90)_7$	14	0.10296E-02	0.10296E-02	0.57570E-02	0.57570E-02	0.67661E-02
$(0/90/0)_3\overline{90}$	15	0.10244E-02	0.10318E-02	0.57371E-02	0.57712E-02	0.67654E-02
$(0/90)_8$	16	0.10304E-02	0.10304E-02	0.57610E-02	0.57610E-02	0.67661E-02

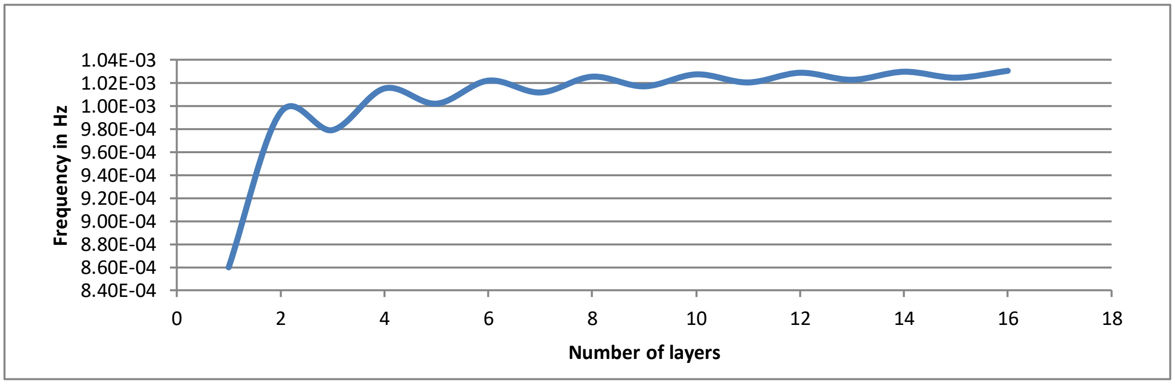


Fig 4.3: A graph of frequency vs no. of layers

4.4.2. Case Study 2: EFFECT OF FIBRE ANGLE ON FREQUENCIESOF CANTILEVER BOX BEAM

The beam with same geometry and material properties as used in previous study has been used. The natural frequencies of the box beam have been tabulated in Table 9. The layup sequence taken is 0/θ/0 where θ has been varied from 15° to 90°. Also, a graph is plotted (Fig. 4.4) to show the nature of change of fundamental frequency. It is observed that with increase in fibre angle, natural frequency increases and reaches maximum for θ =90°. In the initial and last part, the rate of increase in natural frequency is less compared to the middle range for θ =45°, 60°, 75°.

Table 9: Variation of Frequency for different angle of layer

FREQUENCY ANALYSIS FOR VARIATION OF FIBRE ANGLE					
Angle of Layer 0/ θ /0	Frequency in Hz 1st mode	Frequency in Hz 2nd mode	Frequency in Hz 3rd mode	Frequency in Hz 4th mode	Frequency in Hz 5th mode
15°	0.85806E-03	0.93186E-03	0.49553E-02	0.53030E-02	0.68877E-02
30°	0.85996E-03	0.92876E-03	0.49907E-02	0.53223E-02	0.71281E-02
45°	0.87750E-03	0.93881E-03	0.50913E-02	0.53911E-02	0.72329E-02
60°	0.91418E-03	0.96574E-03	0.52608E-02	0.55112E-02	0.71008E-02
75°	0.95783E-03	0.99843E-03	0.54411E-02	0.56331E-02	0.68727E-02
90°	0.97895E-03	0.10138E-02	0.55226E-02	0.56844E-02	0.67639E-02

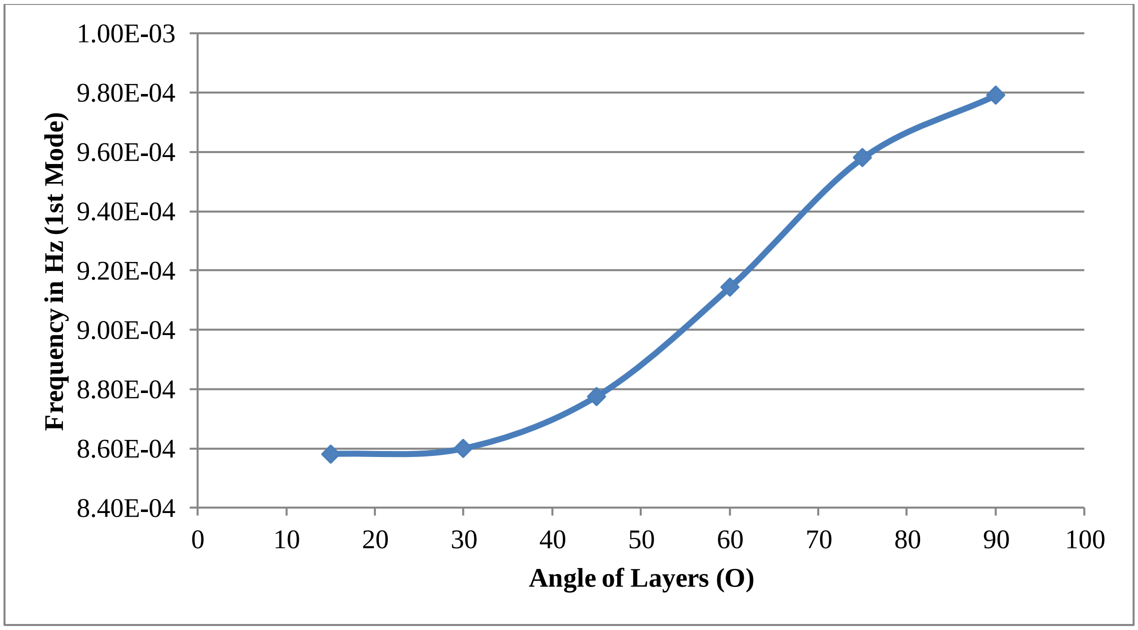


Fig 4.4: A graph of fundamental frequency vs Angle of Layers

4.4.3. Case Study 3: EFFECT OFCORE THICKNESS FOR SANDWICH MATERIAL ON FREQUENCIESOF CANTILEVER BOX BEAM

Here the geometry of the beam kept same as in Fig. 4.2. Sandwich material properties are used where the core (*c*) material properties are related to composite material properties (f) as follows:- $E_{2f}/E_{1c} = E_{2f}/G_{1c} = 27.7$, $\gamma_c = 0.35$

First five natural frequencies of the box beam for different Core thicknesses keeping overall thickness same at 2mm is given in Table 10 along with a graph (Fig. 4.5) showing variation of fundamental frequency for different core thicknesses.

It is observed that the natural frequencies decrease with the increase of core thicknesses of sandwich layer. Generally softer material is used as core material. Keeping the total thickness same, as the thickness of core material increases, the stiffness of structure decreases and hence a reduction in natural frequency occurs.

Table 10: Variation of Frequency for different Core Thickness of Sandwich material

FREQUENCY ANALYSIS (USE OF SANDWICH MATERIAL							
Angle of Layer	Skin Thickness in mm Total thickness t=2mm	Core Thickness in mm Total thickness t=2mm	Frequency in Hz 1st mode	Frequency in Hz 2nd mode	Frequency in Hz 3rd mode	Frequency in Hz 4th mode	Frequency in Hz 5th mode
(0/90/$\bar{0}$)s	0.75	0.5	0.10252E-02	0.10275E-02	0.57100E-02	0.57229E-02	0.65923E-02
(0/90/$\bar{0}$)s	0.625	0.75	0.10174E-02	0.10196E-02	0.56662E-02	0.56775E-02	0.65297E-02
(0/90/$\bar{0}$)s	0.5	1	0.10059E-02	0.10078E-02	0.56053E-02	0.56152E-02	0.64553E-02
(0/90/$\bar{0}$)s	0.375	1.25	0.98733E-03	0.98875E-03	0.55080E-02	0.55162E-02	0.63510E-02
(0/90/$\bar{0}$)s	0.25	1.5	0.95312E-03	0.95407E-03	0.53277E-02	0.53336E-02	0.61745E-02

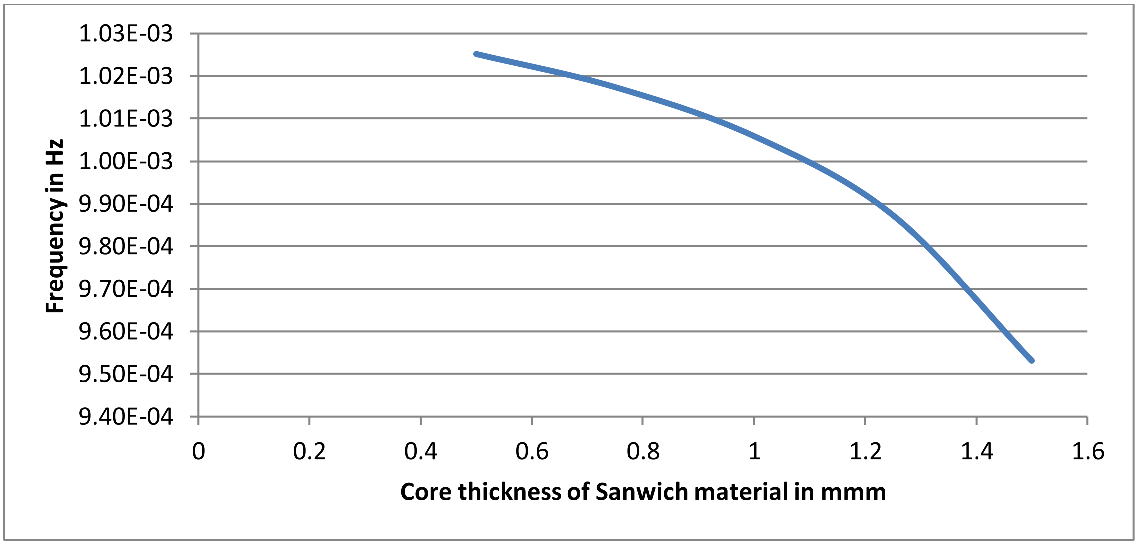


Fig 4.5: A graph of frequency vs Core Thickness of Sandwich material

CHAPTER 5

5.1. Conclusion

Box beam is a very important structural member which is used in aerospace, naval and bridge type structures. Here the Static and free vibration behaviour of laminated composite and sandwich box beam using ANSYS2022 R2 Student version have been studied. Eight noded plate bending element with first order shear deformation theory has been used. Different case studies are done by varying no. of layers, fibre angle orientation, angle of layers and thickness of core material for sandwich material. The following observations can be made.

a. For static and modal analysis, it is observed that undulation in deflection or natural frequencies decreases steadily with the increase of layer of composite material. When number of layers reaches nearly 10, number of layers has no significant effect on the deflection or natural frequency.
b. It is observed that the maximum tip deflection occurs at 45° fibre angle due to least stiffness.
c. For sandwich material construction, when core thicknesses increase keeping overall thickness same, then the core material being softer, reduces the stiffness of the structure. As a result, tip deflection increases and natural frequency decreases.

Hence, it can be concluded that by altering layer numbers, fibre angles of composite material and adjusting the core thicknesses of sandwich material, the static and dynamic characteristics can be changed as required.

5.2 Future Scope of the study

a. Parametric studies can be done for variation in thicknesses for web and flange part of box beam.
b. The analysis can be extended for box beams made up of functionally graded material.
c. The analysis can be extended for analysis under environmental loads.

CHAPTER 6

References:

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