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Finite Element Analysis of Aluminum Plates with First Order Shear Deformation Theory

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ABSTRACT

Thin and thick plates are widely used in mechanical, civil, nuclear and aerospace structures as a basic structural element. So well understanding of the dynamic behavior of these elements is very crucial to the design and performance of mechanical systems.

Variety of methods has been developed to analyze the static and dynamic behavior of plate like structure.

But it is very difficult to analyze with many loads and different material properties.

In this thesis, finite element analysis is performed to analyze the response of plates with different materials such as Structural Steel, Aluminum Alloy, Manganese Steel, and Aramid and compare with that of Functionally Graded Material (FGM) with Aluminum and Ceramic as interface zone. The assumed field displacements equations are represented by a first order shear deformation theory.

Static analysis and thermal analysis is performed on the plates. Analysis is to be performed to compute the deformations, stresses and heat transfer rates for plates. The analysis is performed on plate using shell element for FGM. Theoretical calculations are done to determine properties of FGM at K=2 and K=4.

Modeling is done in Pro/Engineer and Analysis is done in Ansys. Theoretical calculations are done to determine stress, strain, displacement and shear coefficient factor using first order deformation theory.

INTRODUCTION

Mindlin–Reissner plate theory:

The Mindlin–Reissner theory of plates is an extension of Kirchhoff–Love plate theory that takes into account shear deformations through the thickness of a plate. The theory was proposed in 1951 by Raymond Mindlin. A similar, but not identical, theory had been proposed earlier by Eric Reissner in 1945. Both theories are intended for thick plates in which the normal to the mid-surface remains straight but not necessarily perpendicular to the mid-surface.

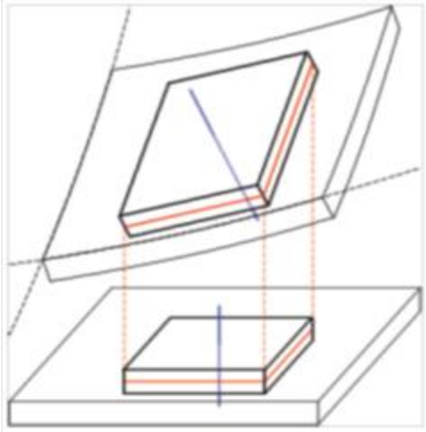

Fig 1.1: Shows deformation of plate highlighting the displacement, the mid-surface (red) and the normal to the mid-surface (blue)

The Mindlin–Reissner theory is used to calculate the deformations and stresses in a plate whose thickness is of the order of one tenth the planar dimensions while the Kirchhoff-Love theory is applicable to thinner plates. The form of Mindlin–Reissner plate theory that is most commonly used is actually due to Mindlin and is more properly called Mindlin plate theory. The Reissner theory is slightly different.

Mindlin theory:

Mindlin's theory was originally derived for isotropic plates using equilibrium considerations. A more general version of the theory based on energy considerations is discussed here.

Stress–strain relations:

The stress–strain relations for an orthotropic material, in matrix form, can be written as

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{23} \\ \sigma_{31} \\ \sigma_{12} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{22} & 0 & 0 & 0 \\ 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{23} \\ \varepsilon_{31} \\ \varepsilon_{12} \end{bmatrix}$$

Where

σ is Stress in a given direction

ε is Strain in a given direction

C is Rigidity modulus in a given direction

Functionally Graded Material (FGM):

In materials science Functionally Graded Material (FGM) may be characterized by the variation in composition and structure gradually over volume, resulting in corresponding changes in the properties of the material. The materials can be designed for specific function and applications. Various approaches based on the bulk (particulate processing), perform processing, layer processing and melt processing are used to fabricate the functionally graded materials.

The basic structural units of FGMs are elements or material ingredients represented by maxel. The term maxel was introduced in 2005 by Rajeev Dwivedi and Radovan Kovacevic at Research Center for Advanced Manufacturing. The attributes of maxel include the location and volume fraction of individual material components.

A maxel is also used in the context of the additive manufacturing processes (such as stereolithography, selective laser sintering, fused deposition modeling, etc.) to describe a physical voxel (a portmanteau of the words 'volume' and 'pixel'), which defines the build resolution of either a rapid prototyping or rapid manufacturing process, or the resolution of a design produced by such fabrication means.

The concept is to make a composite material by varying the microstructure from one material to another material with a specific gradient. This enables the material to have the best of both materials. If it is for thermal, or corrosive resistance or malleability and toughness both strengths of the material may be used to avoid corrosion, fatigue, fracture and stress corrosion cracking.

Modeling and simulation

Numerical methods have been developed for modeling and simulating mechanical behavior of FGM. Methods that allow material property varying continuously in elements was proposed by researchers in Japan in 1990.

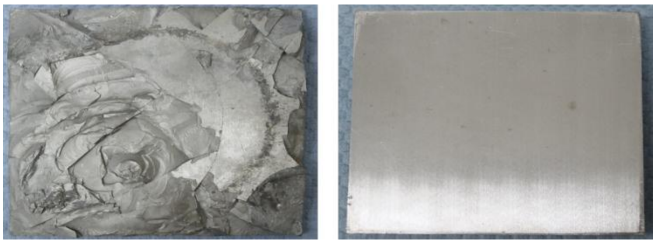

Fig 1.2: Functionally Graded Material (FGM)

Functionally Graded Material (FGM):

Pure metals are of little use in engineering applications because of the demand of conflicting property requirement. For example, an application may require a material that is hard as well as ductile, there is no such material existing in nature. To solve this problem, combination (in molten state) of one metal with other metals or nonmetals is used.

This combination of materials in the molten state is termed alloying (recently referred to as conventional alloying) that gives a property that is different from the parent materials. Bronze, alloy of copper and tin, was the first alloy that appears in human history .Bronze really impacted the world at that time, it was a landmark in human achievement and it is tagged the

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'Bronze Age' in about 4000 BC. Since then, man has been experimenting with one form of alloy or the other with the sole reason of improving properties of material. There is limit to which a material can be dissolved in a solution of another material because of thermodynamic equilibrium limit.

Processing Techniques of FGM

Thin functionally graded materials are usually in the form of surface coatings, there are a wide range of surface deposition processes to choose from depending on the service requirement from the process.

A. Vapor Deposition Technique

Some of the vapor deposition techniques are sputter deposition, Chemical Vapor Deposition and Physical Vapor Deposition. These vapor deposition methods are used to deposit functionally graded surface coatings and they give excellent microstructure, but they can only be used for depositing thin surface coating. They are energy intensive and produce poisonous gases as their byproducts. Other methods used in producing functionally graded coating include: plasma spraying, electro deposition, electrophoresis, Ion Beam Assisted Deposition, Self-Propagating High-temperature Synthesis etc

B. Powder Metallurgy (PM)

Powder metallurgy (PM) technique is used to produce functionally graded material through three basic steps namely: weighing and mixing of powder according to the pre-designed spatial distribution as dictated by the functional requirement, stacking and ramming of the Pre mixed-powders and finally sintering. PM technique gives rise to a stepwise structure. If continuous structure is desired, then centrifugal method is used.

C. Centrifugal Method

Centrifugal method is similar to centrifugal casting where the force of gravity is used through spinning of the mould to form bulk functionally graded material .The graded material is produced in this way because of the difference in material densities and the spinning of the mould. There are other similar processes like centrifugal method in the literature (e.g. gravity method, etc.). Although continuous grading can be achieved using centrifugal method but only cylindrical shapes can be formed. Another problem of centrifugal method is that there is limit to which type of gradient can be produced because the gradient is formed through Centrifugal force and density difference.

D. Solid Free Form (SFF) Fabrication Method

Solid freeform is an additive manufacturing process that offers lots of advantages that include: higher speed of production, less energy intensive, maximum material utilization, ability to produce complex shapes and design freedom as parts are produced directly from CAD (e.g. AutoCAD) data.

E. Die compaction of layers (powder stacking)

In this simple and well established method a gradient is formed by the deposition of powder layers with changing compositions in the compacting die. The disadvantages of the process are obvious: discrete changes, limited number of layers (up to 10 in laboratory scale, but not more than two or three in potential fabrication), limited thickness of individual layers (normally not less than 1 mm), limited size of the part (<100 cm2) due the limits of compaction forces, discontinuous manufacturing with low productivity. Nevertheless this method allows effective laboratory studies of functionally graded systems.

F. Continuous dry deposition of layers

A continuous process for the deposition of the powder mixture with changing compositions on a conveyor belt. Sequential deposition of powders results in a stepped gradient. Therefore a special synchronized distributor was designed which makes a continuous change of the composition feasible.

G. Sheet lamination

Thin sheets with different compositions can be produced by dry or wet powder techniques (powder rolling or tape casting) and joined to form a stepped gradient. Powder rolling is a well developed process giving green sheets with a thickness in the range of 1 mm. Tape casting of very fine powders even allows a sheet thickness in the double-digit micrometer range. The high productivity of the green sheet production offers a high potential for up-scaling by laminating sheets with different compositions. The number of sheets would be limited mainly by the costs of fabrication.

Areas of application of FGM

Some of the applications of functionally graded materials are highlighted below:

- Aerospace
- Medicine
- Defense
- Energy
- Optoelectronics

Introduction to Ansys

Ansys is a general-purpose finite element analysis software package. FEA is a numerical method of deconstructing a complex system into very small pieces called elements. The software implements equations that govern the behaviour of these elements and solves them all; creating a comprehensive explanation of how the system acts as a whole. These results then can be presented in tabulated or graphical forms.

This analysis is used for the design and optimization of a system too complex to analyze by hand. Systems are too complex due to their geometry, scale, or governing equations. With virtual prototyping techniques, users can iterate various scenarios to optimize the product long before the manufacturing is started. This enables a reduction in the level of risk, and in the cost of ineffective designs.

Generic steps to solving any problem in Ansys

Like solving any problem analytically, you need to define

(1) Your solution domain
(2) Divide the physical model in to small elements
(3) Apply the boundary conditions
(4) You then solve the problem and present the results.

LITERATURE SURVEY

The following works are done by some authors on functionally graded material plate.

The work done by Natarajana , a cell based smoothed finite element method with discrete shear gap technique is employed to study the static bending, free vibration, mechanical and thermal buckling behavior of functionally graded material (FGM) plates. The plate kinematics is based on the first order shear deformation theory.

In the work done by Swarup Sahoo, analytical work deals with prediction of the stresses developed in a Functionally Graded Timoshenko Beam that has been reinforced with Carbon Nanotubes (CNTs), which is subjected to thermal and mechanical loads. High temperatures have been applied to the upper and lower surfaces of the beam with a certain temperature difference. In the present study the power law, sigmoid and exponential distribution is considered for the volume fraction distributions of the functionally graded plates.

In the work done by Shabna M.S, flat rectangular plates without cut-out which can be assumed as perfect plates and plates with a central rectangular cut-out that is considered as imperfect plates which are made up of steel, aluminum and invar materials are analyzed. Finally comparison has been done between the results obtained from numerical analysis and ANSYS results for isotropic rectangular plate without cut-out.

In the work done by S Natarajana, the bending and the free flexural vibration behavior of sandwich functionally graded material (FGM) plates are investigated using QUAD-8 shear flexible element developed based on higher order structural theory.

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This theory accounts for the realistic variation of the displacements through the thickness.

Modeling of functionally graded material plate in Pro/Engineer

For modeling of plates, the reference is taken from Marvin Ealiyas Mathews, Shabna M.S,Thermal-Static Structural Analysis of Isotropic Rectangular Plates As specified in References chapter.

500	Plate length mm
500	Plate width mm
60	Plate thickness mm

Table 3.1: Shows the dimensions of the plate

3D Model of functionally graded plate

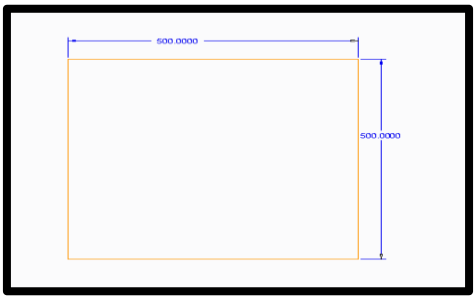

Fig 3.1: 2D Sketch

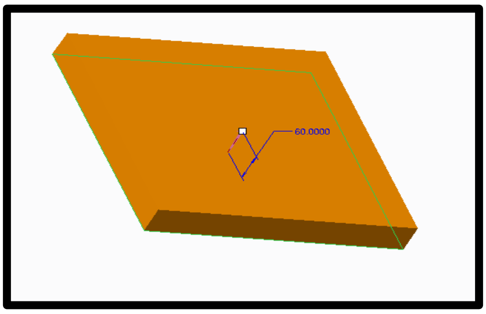

Fig 3.2: Extruded by 60mm to create plate

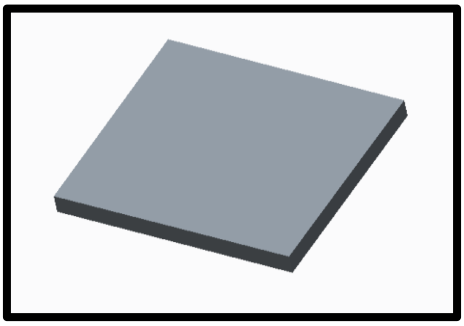

Fig 3.3: Final model of the plate

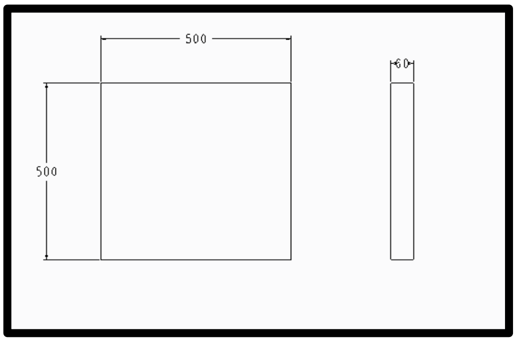

Fig 3.4: 2D drafting of plate

Surface model of FGM plate

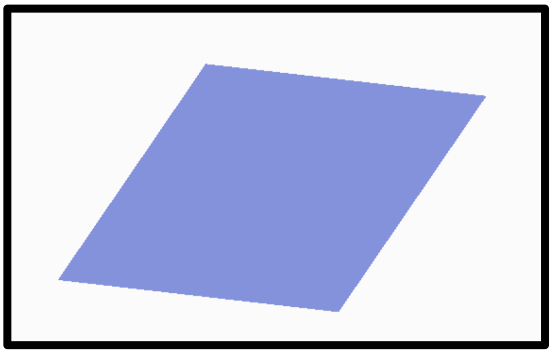

Fig 3.5: Fill to create plate

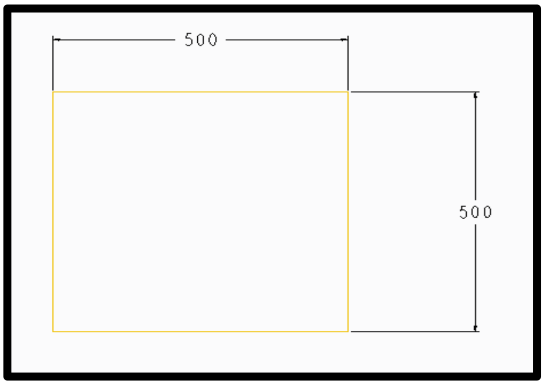

Fig 3.6: 2D drafting of surface plate

Analysis of plate with different materials

Structural analysis of plate with different materials

The FGM plate is analyzed for applied pressure is 20 MPa. The value is taken from the journal paper, Thermal-Static Structural Analysis of Isotropic Rectangular Plates by Mervin Ealiyas Mathews, Shabna M.S, as specified in references.

The material properties specified in the below table were also taken from the same above journal.

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MATERIAL	Poisson's ratio	Young's modulus (GPa)	Density (g/cc)	Allowable Strength (MPa)
STRUCTURAL STEEL	0.26	200	7.87	275
ALUMINUM	0.36	68.0	2.6989	310.26

Table 5.1: Material Properties of structural steel and aluminum

Structural analysis of plate with material as Structural steel

Save the Pro-E Model in .iges format

→Launch Ansys → Workbench→ Select analysis system → static structural → double click →Select geometry → right click → import geometry → select browse →open part → ok

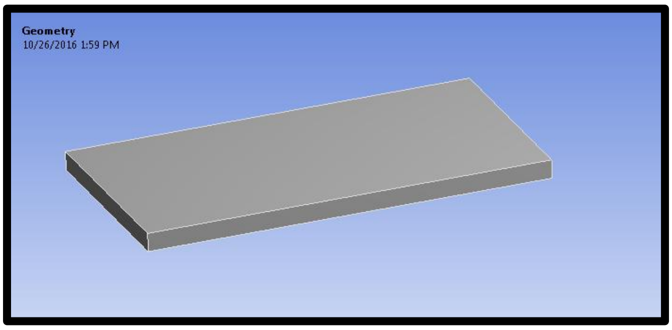

Fig 5.1: Imported model from Pro\Engineer

Select model→right click on it→ select edit→ window will be open in that select mesh→right click on it→select generate mesh

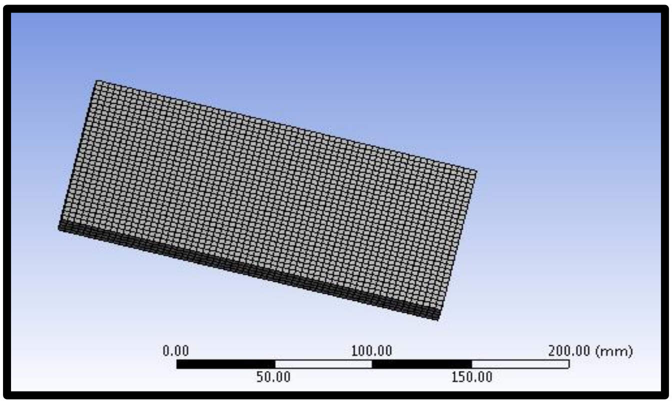

Fig 5.2: Meshed Model

Select static structural →right click on it →insert→ force →select area→ enter magnitude→apply.

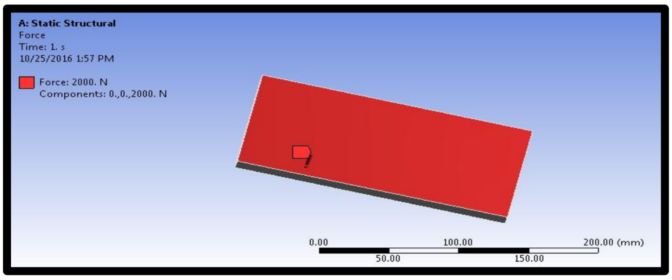

Fig 5.3: Force is applied on the Plate

Select static structural →right click on it →Insert→ Fixed support→select area→apply.

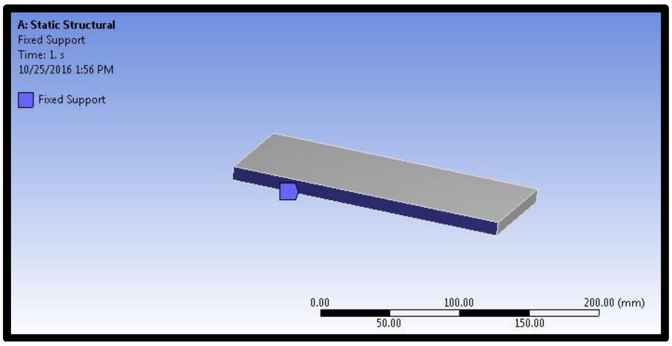

Fig 5.4: Fixed support is applied at sides of the Plate

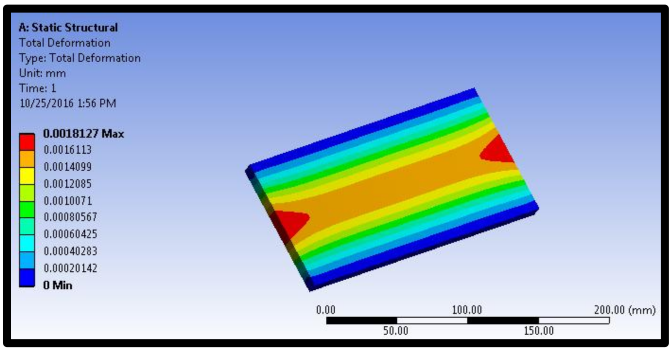

Fig 5.5: Shows the maximum deformation in structural steel is 0.0018127mm

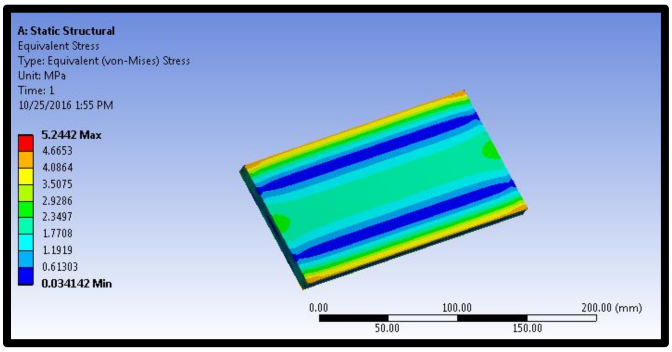

Fig 5.6: Shows the maximum stress in structural steel is 5.2442Mpa

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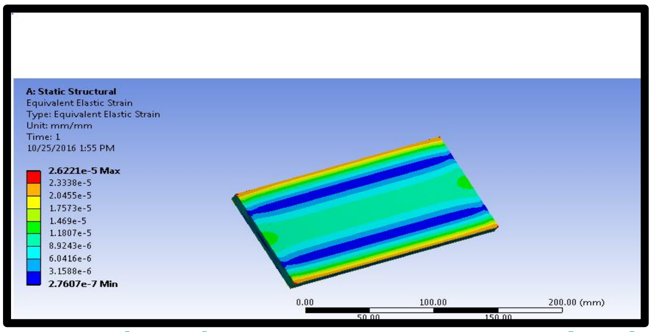

Fig 5.7: Shows the maximum strain in structural steel is 2.6221e-5

Structural analysis of plate with material as Aluminum alloy

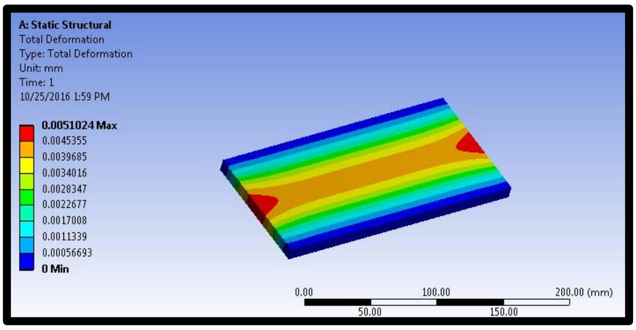

Fig 5.8: Shows the maximum deformation in aluminum alloy is 0.0051024 mm

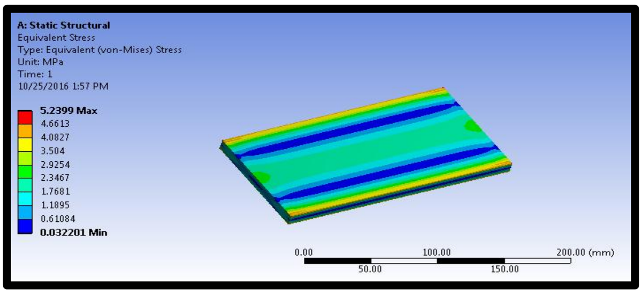

Fig 5.9: Shows the maximum stress in aluminum alloy is 5.2399 Mpa

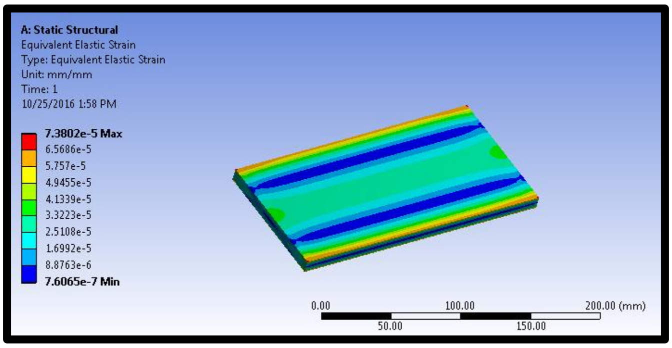

Fig 5.10: Shows the maximum strain in aluminum alloy is 7.3802e-5

Structural analysis of plate with material as Aramid

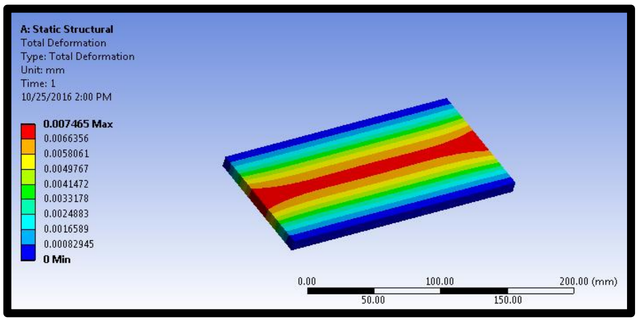

Fig 5.11: Shows the maximum deformation in aramid is 0.007465mm

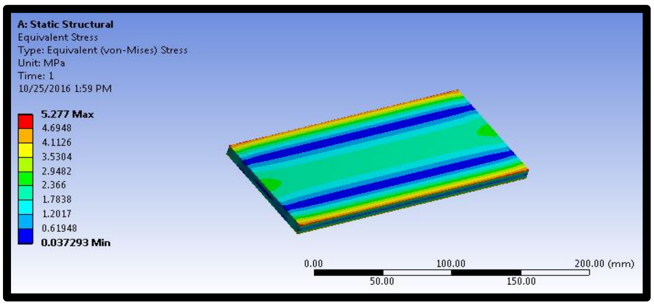

Fig 5.12: Shows the maximum stress in aramid is 5.277Mpa

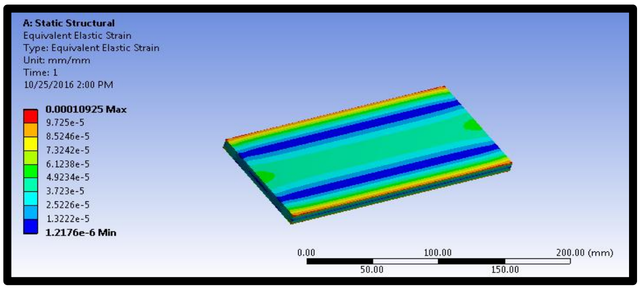

Fig 5.13: Shows the maximum strain in aramid is 0.00010925

Structural analysis of plate with material as Manganese steel

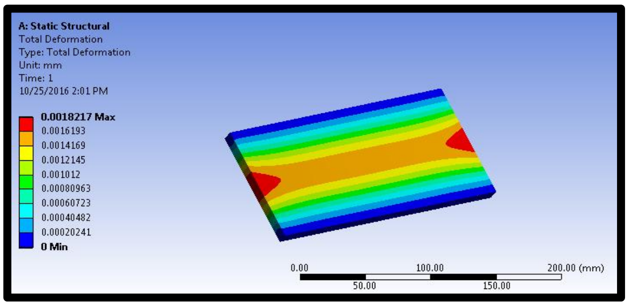

Fig 5.14: Shows the maximum deformation in manganese steel is 0.0018217mm

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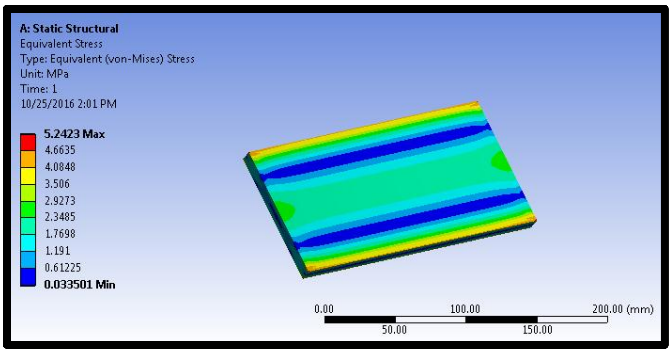

Fig 5.15: Shows the maximum stress in manganese steel is 5.2423Mpa

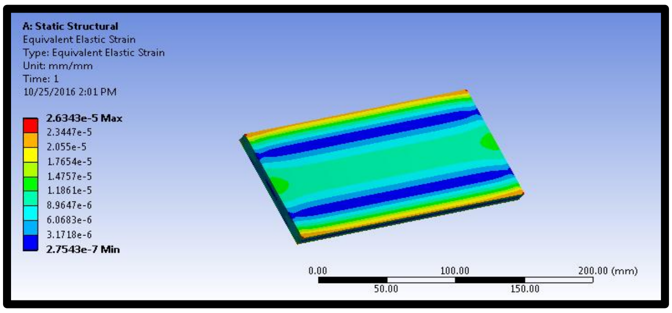

Fig 5.16: Shows the maximum strain in manganese steel is 2.6343e-5

Results and Discussion

Structural analysis of plate with different materials

Material	Stress (MPa)	Deformation (mm)	Strain
Structural steel	5.2442	0.0018127	2.6221e-5
Aluminum alloy	5.2399	0.0051024	7.3802e-5
Aramid	5.277	0.007465	0.00010925
Manganese steel	5.243	0.0018217	2.6343e-5
FGM with K=2	26.711	0.021512	8.4627e-5
FGM with K=4	42.001	0.022863	0.00010143

Table 6.1: Table showing deformation of plate with different material

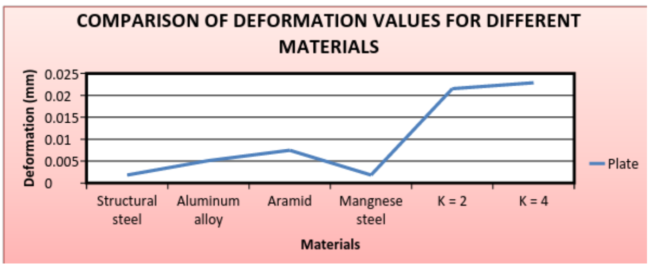

Fig 6.1: Graph showing deformation of plate with different material

By observing the result and graph for deformation values, the values are more when FGM is used than other materials. The deformation is increasing for FGM from K=2 to K=4.

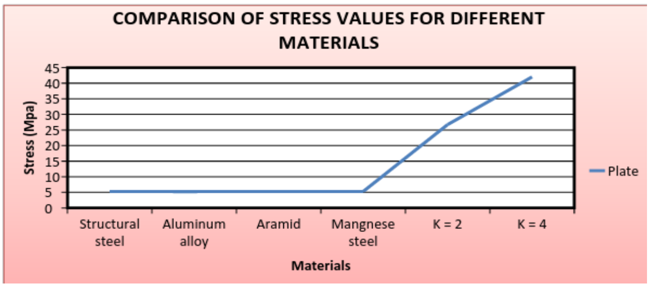

Fig 6.2: Graph showing stress induced in plate with different material

By observing the result and graph for stress values, the values are more when FGM is used than other materials. The stress is increasing for FGM from K=2 to K=4.

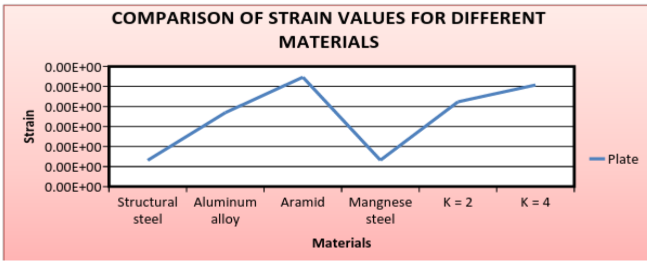

Fig 6.3: Graph showing stress induced in plate with different material

By observing the result and graph for strain values, the values are less when FGM is used than Steel and Aluminum and Aramid but more than Manganese Steel. The strain is increasing for FGM from K=2 to K=4.

CONCLUSION

Static, and Thermal analyses are performed on the plates for Structural Steel and Aluminum using Solid Element and for FGM material with k = 2, and k = 4 using Shell Element and Analysis is done in Ansys.

By observing the structural analysis results, the deformation values are more when FGM is used than other materials. The deformation is increasing from

K=2 to K=4. By observing the results for stress values, the values are more when FGM is used than other materials. The stress is increasing from K=2 to K=4. By observing the result for strain values, the values are less when FGM is used than Steel and Aluminum and Aramid but more than Manganese Steel. The strain is increasing from K=2 to K=4.

By observing the thermal analysis, for heat flux values, the values are more when FGM is used than Steel and Aluminum. The values are increasing from K=2 to K=4. When the heat flux is increased, heat transfer rates are increasing.

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